FRONTEX

Earth Observation for Border Management

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Abbreviations

Abb.	Term	Definition
AIS	Automatic Identification System	An automatic tracking system used on ships and by vessel traffic services for identifying and locating vessels.
CBP	Customs and Border Protection	A U.S. federal law enforcement agency securing borders and facilitating lawful trade and travel.
CBSS	Copernicus Border Surveillance Service	Supports EU member states in border control by providing geospatial information.
DEM	Digital Elevation Model	A representation of the bare ground (bare earth) topographic surface of the Earth.
DHS	Department of Homeland Security	A U.S. federal department responsible for public security.
EDA	European Defence Agency	An agency of the European Union supporting member states' military capability development.
EEZ	Exclusive Economic Zone	A sea zone over which a state has special rights regarding exploration and use of marine resources.
EIBM	European Integrated Border Management	A European Union initiative for integrated management of external borders.
EMPACT	European Multidisciplinary Platform Against Criminal Threats	An EU policy cycle targeting serious and organised crime.
EMSA	European Maritime Safety Agency	An EU agency working to reduce the risk of maritime accidents, pollution and loss of life at sea.
EO	Earth Observation	The gathering of information about the Earth's physical, chemical and biological systems.
EOGS	Earth Observation Governmental Service	Part of Copernicus providing EO information to public authorities.
ESA	European Space Agency	An intergovernmental organisation dedicated to the exploration of space.
EUROSUR	The European Border Surveillance System	A communication system supporting situational awareness and reaction capability at EU borders.
EVI	Enhanced Vegetation Index	An optimised vegetation index minimising soil background influences.
GDPR	General Data Protection Regulation	European Union regulation on data protection and privacy for all individuals within the EU.
GEOINT	Geospatial Intelligence	Intelligence derived from the exploitation and analysis of imagery and geospatial information.
GIS	Geographic Information Systems	A computer system designed to capture, store, manage, analyse and display geographically referenced data.
GNSS	Global Navigation Satellite System	A satellite-based system providing Positioning, Navigation and Timing services.
HAPS	High Altitude Platform Systems	Airborne systems operating in the stratosphere.
LEO	Low Earth Orbit	Earth-centred orbits with an altitude of 2 000 kilometres or less above the surface.
MARSUR	Maritime Surveillance	The monitoring of maritime areas for security or other purposes.
NDVI	Normalised Difference Vegetation Index	A graphical indicator used to analyse remote sensing measurements and assess whether the target contains live green vegetation.
NDWI	Normalised Difference Water Index	A remote sensing-derived index used to delineate open water features and enhance their presence in remotely-sensed imagery.
NIR	Near-Infrared	The portion of the electromagnetic spectrum just beyond visible red light.

Abb.	Term	Definition
RGB	Red Green Blue	A colour space that reproduces the colours visible to the human eye by mixing the three primary colours: red, green, and blue.
RF	Radio Frequency	A measurement representing the oscillation rate of electromagnetic radiation spectrum, or electromagnetic radio waves.
SAR	Synthetic Aperture Radar	A form of radar that creates two-dimensional images or three-dimensional reconstructions of objects.
SatCen	European Union Satellite Centre	An EU agency providing geospatial intelligence from satellite imagery.
SAVI	Soil Adjusted Vegetation Index	A vegetation index minimising soil brightness influences.
SIGINT	Signals Intelligence	Intelligence gathered from electronic signals.
SORA	Specific Operations Risk Assessment	A methodology for assessing risks related to drone operations.
QC4EO	Quantum Computing for Earth Observation	The field of study focused on use of quantum computing for EO purposes.
UAV	Unmanned Aerial Vehicle	An aircraft without a human pilot onboard, also known as a drone.
UNOSAT	United Nations satellite Centre	A UN body providing satellite imagery analysis.
VHF	Very High Frequencies	Radio frequencies from 30 to 300 megahertz.
VHR	Very High Resolution	Refers to images with high spatial resolution.
VLEO	Very Low Earth Orbit	An orbit around Earth with a very low altitude.
VMS	Vessel Monitoring Systems	Systems used to track the positions and movements of vessels.

1. Introduction

1.1 About Frontex

The mission of Frontex, the European Border and Coast Guard Agency, is to ensure coherent European integrated border management by facilitating and rendering more effective the application of existing and future Union measures relating to the management of the EU's external borders, in accordance with its tasks and with full respect for the Union acquis on fundamental rights, international law, and Code of Conduct (CoC). The European Border and Coast Guard Agency (Frontex) is governed by Regulation (EU) 2019/1896 of 13 November 2019 on the European Border and Coast Guard (OJ L 295, 14.11.2019, p. 1).

More about Frontex's origin, organisation, its mandate, fields of activity, strategy and planned activities, and especially Frontex Work Programmes can be found in the official information section published on the Frontex website.[1]

1.1.1 Frontex and Copernicus

Since 2015 Frontex has been entrusted by the European Commission to provide the Copernicus Border Surveillance Service (CBSS) to national border management authorities. The service utilises Earth observation data to provide critical support in tackling irregular migration and cross-border crime. As the operator of the CBSS on behalf of the European Commission, Frontex provides a single point of entry for the acquisition, fusion, and delivery of border surveillance services, and works closely with national authorities, and other stakeholders to ensure the effective provision of services and information products. Frontex's expertise and capabilities are enhanced by the Copernicus Programme, which provides access to Earth observation data that is enriched with other data sources to create tailored products and services, such as reports, maps, and interactive tools, designed to meet the evolving needs of end-users. Through its partnerships with the Directorate-General for Defence Industry and Space (DG DEFIS), Frontex is able to leverage the CBSS to deliver high-quality Earth Observation (EO) data and support border management activities. As a key player in the EU's integrated border management framework, Frontex is committed to continually developing and improving the CBSS, ensuring it remains aligned with the latest technological advancements and end-user requirements, and actively participates in strategic research priorities in the Copernicus domain, providing feedback and expertise to inform the development of new services and technologies, ultimately contributing to a more secure and efficient management of the EU's external borders. By harnessing the capabilities of the CBSS, Frontex is able to enhance its support for national border management authorities.

1.1.2 Copernicus Border Management Service

The Copernicus Border Surveillance Service represents a critical advancement within the context of European Integrated Border Management (EIBM), significantly enhancing the European Union's ability to manage and secure its external borders. Operated under the umbrella of Copernicus Security Services, CBSS uses advanced Earth Observation capabilities from satellite and aerial systems, delivering comprehensive, timely and actionable intelligence to border authorities. Its primary objective is to enhance situational awareness, optimise operational decision-making and strengthen the strategic and tactical response to a wide range of security challenges confronting the European borders.

CBSS employs diverse satellite-based Earth Observation technologies including open access Copernicus data, high-resolution commercial optical imagery, Synthetic Aperture Radar (SAR) and infrared sensors. These capabilities are used for critical border surveillance activities such as tracking illegal maritime activities, detecting irregular migration flows and monitoring movements across remote and challenging terrain.

[1] *Frontex | European Union Agency*

Its advanced analytical capabilities support real-time detection, identification and tracking of mobile targets, including vessels, vehicles and also individuals. Moreover, CBSS significantly aids in maritime border surveillance, search and rescue operations, border control and security monitoring, and the identification of cross-border criminal activity.

CBSS also supports operations during humanitarian crises and natural disasters by providing rapid and detailed environmental assessments, thus enhancing crisis management and emergency response capabilities. The service is instrumental in monitoring geopolitical developments, particularly in conflict zones and regions characterised by instability or significant migratory pressure, ensuring that the EU's border control measures remain responsive, effective, and in line with humanitarian principles.

Ultimately, CBSS exemplifies a future-oriented vision for border surveillance, using cutting-edge Earth Observation capabilities and integrated intelligence-driven strategies. This comprehensive approach not only fortifies the EU's border management but also aligns operational activities with fundamental human rights principles, laying a solid foundation for a secure, resilient and responsive European border management strategy in the years ahead.

1.2 About the Report

The purpose of this report is to inform readers about the capabilities and limitations of EO technologies for enhancing border security. It aims to provide an understanding of how EO can be leveraged to address various border-related challenges, from detecting illegal crossing and smuggling activities to supporting humanitarian efforts like search and rescue operations. By presenting detailed use cases, identifying operational gaps and suggesting emerging trends and recommendations, the report seeks to guide the implementation of EO technologies for more effective border management.

This report analyses the prospective use of EO in border management, evaluates current gaps and assesses technological trends along with alternative technologies. EO technologies include various sensors such as optical, Synthetic Aperture Radar, hyperspectral, thermal infrared, Automatic Identification System (AIS) and Radio Frequencies (RF), and various platforms: satellites, Unmanned Aerial Vehicles (UAVs) and High Altitude Platform Systems (HAPS), detailing their key characteristics, strengths and limitations.

The report also includes six use cases for border surveillance such as maritime border surveillance, vessel detection and tracking, coastal and pre-frontier monitoring, cross-border crime monitoring, land border surveillance and monitoring of irregular migration. For each use case, a SWOT analysis is provided. Finally, the report discusses challenges and limitations in EO-based border management, and emerging trends in this domain.

2. Earth Observation technology overview for border management

Earth Observation technologies are transforming border management by providing remote, timely surveillance over vast and inaccessible areas. Satellite sensors and related systems – from high-resolution optical imagers to radar and ship tracking beacons – enable border agencies to continuously monitor land and maritime frontiers. These tools enhance situational awareness, help intercept illegal activities and even support humanitarian efforts (e.g. rescuing migrants in distress). This review presents an overview of key EO technologies used in border management and security applications.

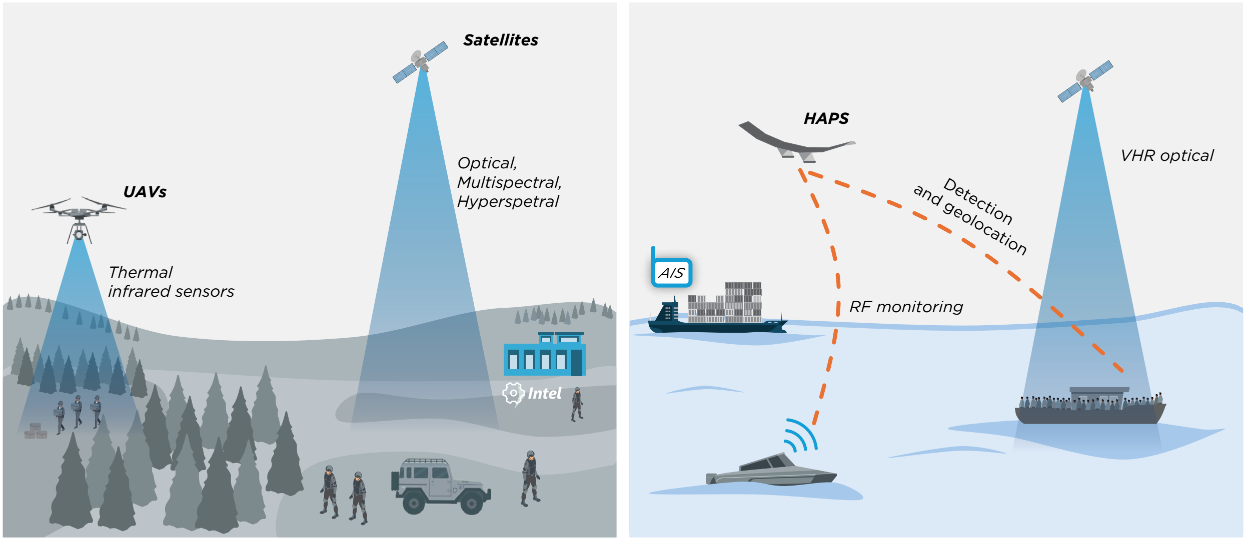

Figure 1. Illustrative representation of various Earth Observation technologies and platforms in border monitoring.

Border surveillance today leverages a suite of EO technologies, each offering unique capabilities. Table 1 summarises the main EO data sources and their relevance to border management:

	EO technology	Key characteristics	Typical resolution	Technical strengths	Key border management applications
Sensors					
Passive sensing	Very High Resolution (VHR) Optical	Multispectral (RGB/NIR), daytime imagery	<1 meter[2]	High spatial detail, clear visual identification	Detailed surveillance (vehicles, personnel, infrastructure), small-boat identification
	Medium Resolution Optical	Multispectral, frequent revisits	10[3]–30[4] meters	Broad-area monitoring	Monitoring large-scale border areas, assessing trends, infrastructure mapping, large-scale movements
	Hyperspectral Imaging	Numerous spectral bands (>100), material detection via spectral signatures	5[5]–30[6] meters	Identifies camouflaged targets and subtle environmental changes; chemical and material detection	Illicit crop identification, hidden object detection, terrain disturbance detection
	Thermal Infrared Sensors	Heat-sensitive imagery; detects thermal signatures day/night	30–100 meters (typically moderate resolution)[7]	Identifies heat emissions from humans, vehicles and active vessels at night or in poor visibility	Nighttime vessel and personnel detection, refugee/migrant camps detection, cross-border activity monitoring
	AIS	Vessel transponder signals; near-real-time maritime data	Vessel-level positioning accuracy (~10 m)[8]	Continuous tracking of vessels at sea; identifies suspicious maritime activities and AIS-off (“dark”) vessels	Maritime security, interdiction support, vessel anomaly detection
Active sensing	SAR	Active radar imaging, day/night, all-weather capability	down to 25 cm[9]	Penetrates clouds, reliable night coverage, excellent vessel detection at sea	Maritime border surveillance, vessel tracking, detecting land border changes, illegal activity detection

2 Maxar. “Clarity and confidence” by Maxar, 2025. https://go.maxar.com/Imagery-Leadership-Spatial-Resolution

3 Satellite Imaging Corporation. “Satellite Imaging Corporation. Sentinel-2A Satellite Sensor (10m)” by Satellite Imaging Corporation. https://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/sentinel-2a/

4 NASA Landsat Science. “Landsat 8” by NASA. https://landsat.gsfc.nasa.gov/satellites/landsat-8/

5 pixxel. “Hyperspectral imagery” by pixxel. https://www.pixxel.space/hyperspectral-imagery

6 eoPortal. “Hyperspectral Imaging” by Herbert J. Kramer, August 2023. https://www.eoportal.org/other-space-activities/hyperspectral-imaging#references

7 Jou-Claus, S., Folch, A., and Garcia-Orellana, J.: Applicability of Landsat 8 thermal infrared sensor for identifying submarine groundwater discharge springs in the Mediterranean Sea basin, Hydrol. Earth Syst. Sci., 25, 4789–4805, https://doi.org/10.5194/hess-25-4789-2021, 2021.

8 International Maritime Organisation. “Revised guidelines for the onboard operational use of shipborne automatic identification systems (AIS).” Resolution A.1106(29), 2015. https://www.classnk.or.jp/hp/pdf/activities/statutory/ism/imo/imo_a1106-29.pdf

9 EUSI. “What is SAR Imagery? Introduction to Synthetic Aperture Radar”, 2024. https://www.euspaceimaging.com/blog/2024/04/05/what-is-sar-imagery/

	EO technology	Key characteristics	Typical resolution	Technical strengths	Key border management applications
Passive or Active	RF sensors	Detection and geolocation of unauthorised communication devices[10]	N/A	Transmitters can detect and geolocate from long distances in all weather conditions without the need for direct visual confirmation of the target.	Identification of terrorist networks, detection of non-cooperative vessels or aircraft, geolocation of RF emitters, search and rescue support spectrum surveillance and signal interception,
Platforms					
Passive and Active	Satellites	Space-based observational platforms orbiting Earth	30 cm - 30 m	Broad area coverage; frequent revisits; long operational life.	Continuous large-scale monitoring; detection of unauthorised crossings and infrastructure changes; enabling strategic planning and analysis.
	UAVs and HAPS	Persistent surveillance aerial platforms (balloons, UAV, airships) equipped with optical/SAR/ thermal sensors	Several cm[11]	Persistent localised surveillance; rapid deployment; flexible sensor payload	Gap-filling in satellite coverage, rapid incident response, continuous detailed surveillance of border hotspots

Table 1. Overview of technologies for border management.

The technologies summarised above provide complementary capabilities essential for contemporary border management. Each has unique strengths and limitations, underscoring the importance of integrating multiple sensor types and platforms to achieve comprehensive and effective border surveillance. Below is an expanded description of these key technologies and their practical applications:

Sensors

VHR optical imagery

Satellite data at very high spatial resolutions (below 1 meter) allows accurate analysis of objects, such as identifying individuals, vehicles, infrastructure and small vessels during daytime conditions. However, optical imagery faces limitations due to weather conditions (clouds, fog) and lack of nighttime capability.

Medium resolution optical imagery

Medium-resolution satellites (e.g. Sentinel-2) provide frequent global coverage at resolutions of approximately 10–30 meters, ideal for broad-scale analysis of large border areas. These data are effective for identifying migration routes, mass movements and significant infrastructure developments, and are particularly useful for long-term monitoring.

[10] Rhode&Schwarz. "Securing borders, safeguarding futures: The critical role of RF sensors" by Rhode&Schwarz. https://www.rohde-schwarz.com/solutions/aerospace-and-defense/multi-domain/border-security/border-security_258207.html?change_c=true

[11] GEONADIR. "What is the resolution of drone mapping?" by Dr Karen Joyce February 2022. https://geonadir.com/drone-resolution/

SAR

SAR satellites (e.g. Sentinel-1[12]) emit radar waves and detect reflections, allowing for all-weather, day/night surveillance. Their primary advantage is the ability to capture imagery through clouds, fog and darkness, making SAR indispensable for maritime border surveillance and land border change detection. SAR data frequently identifies vessel movements, including smaller non-cooperative or dark vessels.

Hyperspectral imaging

Hyperspectral sensors collect data across hundreds of spectral bands, enabling identification of subtle differences in material composition. This capability allows detection of hidden or camouflaged activities such as trails, campsites, illicit crop cultivation or terrain disturbances indicative of human activity, providing insights beyond visual imagery alone.

AIS

AIS provides near-real-time positional and identity data from vessels broadcasting their status and location. Satellite-based AIS is especially useful in monitoring vessel traffic beyond coastal radar range, rapidly identifying anomalies, suspicious activities or dark vessels that disable their AIS transponders to avoid detection.

Thermal infrared sensors

These sensors detect heat emissions from humans, vessels and vehicles, operating effectively day or night. Satellite-based thermal infrared sensors (such as those onboard Sentinel-3) can identify vessels' lights or land-based fires, enabling surveillance operations in poor visibility conditions, such as night or fog, significantly enhancing detection capability.

RF sensor

RF sensors passively detect and geolocate electromagnetic emissions across the radio frequency spectrum, including communication signals and marine radar. Unlike optical or radar sensors, RF sensors identify the presence and behaviour of non-cooperative targets, such as vessels or vehicles that have turned off their transponders, by monitoring signal activity. Space-based RF systems can cover vast maritime and land border areas, enabling detection of illicit activities like smuggling, illegal fishing and unauthorised crossings. By correlating RF detections with AIS and other data sources, RF sensors enhance situational awareness, especially in areas where visual or radar coverage is limited or ineffective.

The diverse array of sensors available today offers unparalleled flexibility in tailoring technology to fit various use cases and applications. Each sensor comes equipped with distinct capabilities and inherent limitations that must be considered to optimise performance. As illustrated in Figure 2, coverage variances among sensors depend heavily on factors such as sensor type, image swath, and camera resolution.

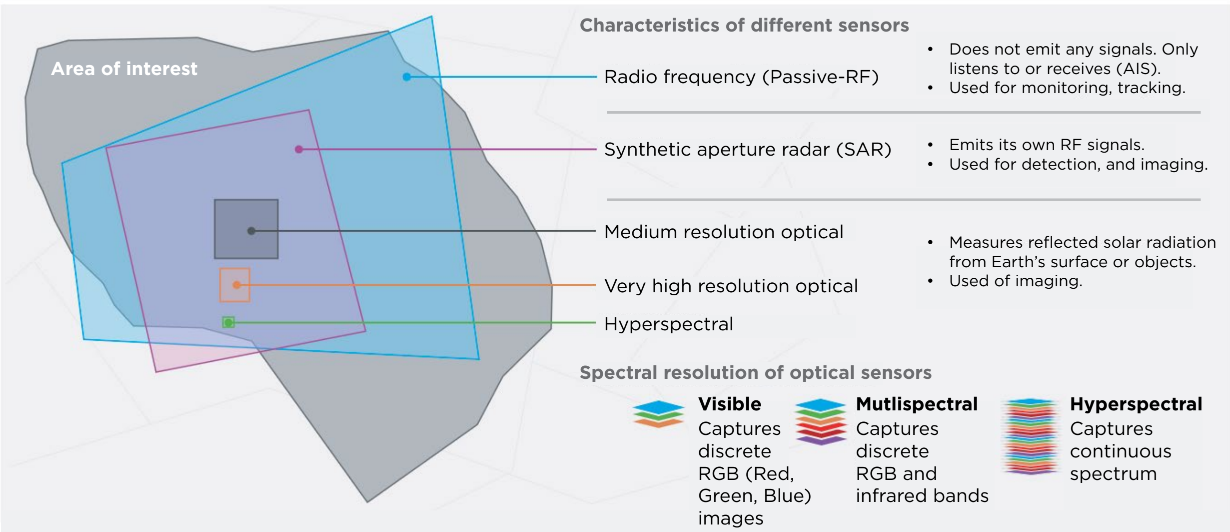

Figure 2. Illustrative representation of sensors' coverage and other characteristics.

[12] ESA. "Sentinel-1 - Radar vision for Copernicus" by ESA. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1

Platforms

Satellites

Satellites orbit the Earth to provide extensive observational capabilities across vast geographical areas. Equipped with advanced optical, SAR and thermal sensors, they offer consistent coverage and frequent revisit times. Satellites play a crucial role in border management by providing comprehensive monitoring and strategic insights. They deliver large-scale, high-resolution imagery crucial for long-term planning, environmental assessments and detecting unauthorised activities. Their broad perspective complements localised aerial observations, ensuring integrated and informed decision-making in border security operations.

Aerial Platforms

Aerial platforms, including aircraft, UAVs and HAPS (stratospheric balloons, airships or fixed wings), carry various sensors (optical, SAR, thermal) offering persistent surveillance capability. Aircraft, UAVs and HAPS provide high-resolution, continuous monitoring over critical border regions, bridging temporal and spatial gaps inherent in satellite-based observations. Their rapid deployment capability complements satellite data, offering near-real-time actionable intelligence and improved operational responsiveness.

3. Use cases and applications of Earth Observation in border management

Earth Observation and detection technologies offer significant capabilities in various border management scenarios. Table 2 elaborates on specific use cases, highlighting the technologies and their gaps and limitations.

Area	Technologies used	Gaps and limitations
Maritime border surveillance	• SAR • AIS • VHR optical imagery • RF sensors	Limited real-time data availability, latency issues, difficulty identifying small vessels ("dark vessels"), RF signal complexity and interpretation
Vessel detection and tracking	• SAR • AIS • VHR optical imagery • AI-driven analytics • HAPS • RF sensors	Limited AIS integration for "dark vessels" and “spoofing vessels,”, false positive data accuracy.
Coastal and pre-frontier monitoring	• SAR • VHR optical imagery • AIS • UAVs • HAPS • RF sensors	Limited predictive capabilities, real-time threat identification

Area	Technologies used	Gaps and limitations
Cross-border crime monitoring	• Hyperspectral imaging • VHR optical imagery • SAR • Digital Twin	Limited spatial resolution (hyperspectral), difficulty detecting camouflaged objects, integration challenges with local intelligence
Land border surveillance	• SAR • Optical imagery • UAVs • HAPS • Change detection algorithms	Limited revisit frequency, challenges in identifying small-scale changes, integrating satellite data with ground sensor data
Monitoring irregular migration	• VHR optical imagery • SAR • Thermal IR • UAVs • HAPS	Limited revisit and real-time response capabilities, reliance on supplementary ground intelligence, difficulties in detecting very small boats

Table 2. Earth Observation use case for border management.

3.1 Maritime border surveillance

Context

Maritime border surveillance is a critical use case for EO technologies due to the vast oceans and coastlines that are difficult to patrol solely with ships or aircraft. Approximately 90% of world trade is transported by ship, making maritime transport a vital facilitator of the global economy. As the shipping industry stands at the forefront of the global supply chain, it drives multiple sectors such as trade, tourism and fisheries.[13] Given this crucial role, ensuring the security and safety of maritime transport is paramount.

Satellites provide an “eye in the sky” to monitor expansive sea areas for unauthorised vessels, illicit activities or vessels in distress.[14] For instance, Copernicus Maritime Surveillance provides services such as maritime safety, maritime security, customs, law enforcement, marine pollution monitoring, fisheries control and international cooperation.

Maritime border surveillance leverages a multi-faceted approach that integrates data from SAR and optical satellites with AIS information. This combination maximises maritime domain awareness by providing precise, all-weather, day-and-night monitoring capabilities. Advanced machine learning algorithms are employed to classify vessel types and predict routes, increasing the efficiency of threat detection and interception. Additionally, historical data analytics allow for pattern recognition and anomaly detection, vital for identifying suspicious activities over time.

[13] EMSA. “Discover the EU Maritime Profile” by EMSA. https://www.emsa.europa.eu/eumaritimeprofile.html

[14] SSPI. “How Satellites Secure the Border” by SSPI. https://www.sspi.org/cpages/how-satellites-secure-the-border

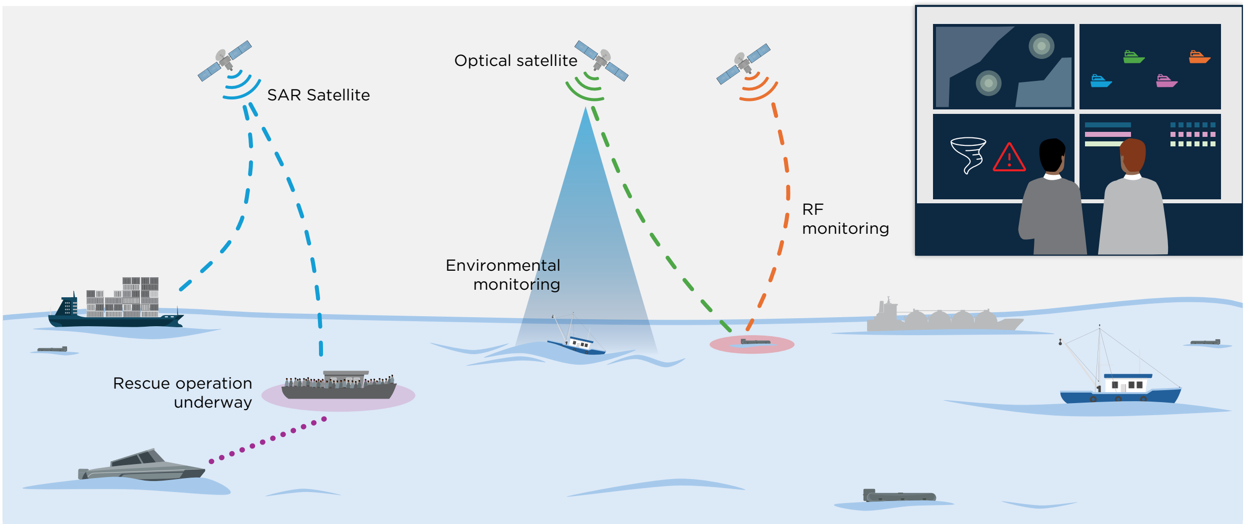

Figure 3. Visual representation of the "Maritime border surveillance" use case.

User needs

To fully leverage maritime surveillance capabilities, users require **real-time data integration, fusion and analysis** for decision-making process. Advanced **visualisation tools and intuitive user interfaces** are essential for end-users to interpret complex data efficiently and respond accordingly. Security agencies also need capabilities for **predictive analytics** to foresee and mitigate potential threats such as abruptly changing environmental conditions. Furthermore, **interoperability with existing maritime systems** is crucial for collaborative international operations.

Adoption level in the EU

The adoption of EO technologies in maritime border surveillance is highly integrated within EU border management practices, particularly within the operations of Frontex and when it comes to maritime surveillance is carried out by the European Maritime Safety Agency (EMSA) . There is increased governmental and institutional support for EO initiatives, illustrated by projects such as the EU's Copernicus programme.

EO technologies

- **SAR -** allows for the detection and monitoring of "dark vessels", vessels that operate without active transponders, like AIS. SARs penetrate clouds and perform nighttime imaging, ensuring continuous observation of maritime areas, enabling the identification of vessels and their movements under challenging atmospheric conditions. Moreover, SAR is crucial for assessing maritime environments, providing detailed insights into ocean phenomena and the positions and types of vessels present.
- **Optical sensors -** these sensors capture images that serve as a visual complement to SAR data, enriching vessel monitoring and surveillance. Optical imagery offers crucial details such as vessel shape, colour and possible markings, aiding in the verification of ship activities and enhancing identification processes. While dependent on daylight and clear conditions, optical sensors provide critical supplementary data that can support SAR findings and refine vessel classification and activity analysis in the maritime domain.
- **RF monitoring –** this technology focuses on capturing and analysing the radio frequency emissions from ships, including those that have disabled their AIS transponders deliberately to conceal their presence. RF monitoring excels in detecting and categorising signals originating from ships' communication and navigation systems, thus bolstering tracking capabilities. It provides an additional layer of maritime awareness by pinpointing vessels that might be uncooperative or deceptive, attempting to evade detection. RF monitoring's strength lies in its ability to recognise and track vessels based on emitted signals, contributing to comprehensive surveillance and risk assessment.
- **Advanced data analytics -** employing artificial intelligence, machine learning, and data fusion techniques, advanced data analytics revolutionises maritime border surveillance by enabling enhanced data processing and anomaly detection. These systems analyse large volumes of diverse datasets to identify unexpected patterns or deviations in vessel behaviour. By automating the analysis, these tools provide real-time insights and predictions, supporting proactive decision-making and strategic resource allocation in maritime security operations.
- **Data integration platforms -** these platforms play a pivotal role in synthesising satellite imagery with AIS data and other sensor inputs, creating an

overview of maritime activity. By integrating various data streams, they enrich situational awareness and streamline information flow. These platforms enable the aggregation of visual, RF and navigational data, providing stakeholders with an integrated, real-time maritime picture that enhances border management and threat response capabilities.

Gaps and limitations

- Limited real-time data availability - while advances in satellite technology have improved data collection, there are still challenges relating to the real-time availability of EO data. Data transmission and processing delays can hinder agencies' ability to make timely decisions during critical situations.
- Latency issues - real-time data processing still faces challenges due to network bandwidth and computational limitations, affecting real-time response.
- Difficulty identifying small vessels - small vessels, particularly those that do not emit AIS signals, pose a significant challenge to detection. Their small size, low profile and potential use of stealth measures make it difficult for even advanced sensors to reliably identify and track them.
- RF signal complexity and interpretation - RF monitoring is challenged by the complexity of analysing and interpreting diverse radio frequency signals emitted by maritime vessels. The wide range of signal types, frequencies and potential interference sources complicates identification and classification of targets. This complexity necessitates advanced signal processing capabilities and robust algorithms to filter out noise, mitigate interference and accurately differentiate between legitimate, deceptive and illicit signals.

Key applications

- Wide-area sea monitoring - satellites can cover huge expanses (e.g. Greece's 13,676 km coastline and the stretches to the Exclusive Economic Zone- EEZ) that would be impossible to continuously patrol otherwise. In fact, for countries like Greece, the optimal means of monitoring such a vast maritime domain is satellite technology. Space-based sensors scan for ships far from shore, giving early warning of incoming vessels.
- Illegal fishing[15] and smuggling - EO data helps spot suspicious vessel behaviour in a country's Exclusive Economic Zone. Radar satellites and RF sensors can detect ships that have turned off AIS – a common tactic of smugglers or illegal fishing boats. By comparing satellite detections with AIS, authorities can flag uncooperative vessels for interception.[16]
- Maritime search & rescue - during irregular migration crises, EO imagery has been used to locate migrant boats in distress. For example, in one case a satellite detected four rubber boats carrying migrants off the Libyan coast, data which was promptly relayed to rescuers and led to 370 people being saved from the Mediterranean. This demonstrates the life-saving impact of satellite surveillance in maritime emergencies.

[15] Following REGULATION (EU) 2019/1896 National authorities carrying out coast guard functions are responsible for a wide range of tasks, which may include maritime safety, security, search and rescue, border control, fisheries control, customs control, general law enforcement and environmental protection.

[16] MaritimeFairTrade. "Using Satellite Images To Fight Cross-Border Maritime Crimes" by Lee Kok Leong, September 2019. *https://maritimefairtrade.org/using-satellite-images-to-fight-cross-border-maritime-crimes*

SWOT analysis

STRENGTH	WEAKNESS	OPPORTUNITIES	THREATS
High coverage, efficient SAR and AIS integration	Limited real-time response, optical sensor weather dependency	Emerging satellite constellations, advanced AI analytics	Cybersecurity vulnerabilities, detection avoidance by small vessels

Case studies

Satellite surveillance: A game changer for Europe's southern border – Greece

Europe's southern border faces significant challenges from irregular migration by sea and maritime smuggling. Since 2015, Frontex has leveraged the EU's Copernicus EO programme to address these issues. A notable success occurred in December 2015, when the Italian authorities using Copernicus/EUROSUR Fusion Service data, provided by Frontex, intercepted the vessel Munzur, smuggling narcotics. Satellite imagery had helped track this ship's movements, leading to the seizure of 13 tonnes of drugs onboard. This case proved the value of satellite surveillance in targeting high-value smuggling operations. The same winter, the new Vessel Detection Service detected a boat carrying 370 people off Libya (as mentioned earlier), allowing all those lives to be saved. These early wins built confidence in satellite support, and by 2017-2018 a series of successes followed: the Golendri and Falkvag ships carrying millions of euro worth of contraband cigarettes were tracked via Copernicus imagery and intercepted, and in March 2018 the Greek Coast Guard, tipped off by satellite optical images of suspicious cargo loading, caught the vessel Daslis with €4.7 million in smuggled goods.[17,18,19]

Help from above: Using satellites to manage migration in Melilla – Spain

In Spain's North African enclave of Melilla, VHR satellite imagery is used to monitor the tight border fence and the surrounding Moroccan territory. European Space Imaging reports that 30 cm resolution images have been instrumental in locating migrant encampments in the hills and tracking movements of large groups before they rush the fence. This information helps Spanish and Moroccan authorities coordinate responses to mass crossing attempts, reducing injuries and saving lives by anticipating dangerous rushes. The Melilla case also showed a humanitarian dimension: identifying unsanitary camps allowed aid groups to assist migrants before desperate crossings turned tragic. Overall, Europe's experience illustrates a comprehensive integration of EO, on land and sea, yielding measurable outcomes measured in lives saved, contraband seized and higher situational awareness at borders.[20]

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17 Copernicus. "Observer: Copernicus - eyes on the EU's external borders", June 2019. https://www.copernicus.eu/en/observer-copernicus-eyes-on-EU-external-borders

18 Frontex. "Boat carrying 13 tonnes of drugs intercepted as part of Operation Triton" by Frontex, December 2015. https://www.frontex.europa.eu/media-centre/news/news-release/boat-carrying-13-tonnes-of-drugs-intercepted-as-part-of-operation-triton-QBbcCa

19 MaritimeFairTrade. "Using Satellite Images To Fight Cross-Border Maritime Crimes" by Lee Kok Leong, September 2019. https://maritimefairtrade.org/using-satellite-images-to-fight-cross-border-maritime-crimes/

20 EUSI. "Border Control in Melilla: A Very High Resolution Look" by European Space Imaging, January 2019. https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/

3.2 Vessel detection and tracking

Context

Vessel tracking is vital for maritime security, especially for countries with vast coastlines. While the AIS helps track ships, it's vulnerable to manipulation by "dark vessels" intentionally hiding their location or identity for illicit activities.

EO technologies provide various solutions, detecting these vessels even when they try to stay hidden. EO uses a combination of satellite-based tools like SAR, optical imagery and RF monitoring to observe vast ocean areas, far exceeding the capabilities of traditional surveillance methods like aircraft. This comprehensive view, often complemented by localised data from HAPS and UAVs, allows authorities to identify and track suspicious vessels, analyse traffic patterns and respond to threats more effectively.

Consider the limitations of traditional surveillance: an aircraft can only survey a fraction of the area covered by a single satellite pass. This difference in coverage highlights the unparalleled advantage of EO in achieving persistent maritime surveillance. The ability to detect dark vessels, analyse traffic patterns and identify anomalies makes EO invaluable for combating illicit activities, securing critical infrastructure and improving search and rescue operations.

User needs

Users require comprehensive maritime visibility to distinguish between legitimate maritime traffic and potential threats. This includes **high-resolution, all-weather radar imaging; RF signal detection; integrated data fusion systems** for making real-time data-based decisions; and **predictive analytics** tools for identifying suspicious vessel behaviour. Users also need **interoperability between EO systems and existing maritime security infrastructure,** as well as scalable solutions that adapt to evolving threats. **Access to fresh data and user-friendly platforms** to interpret data efficiently are crucial for enabling timely decision-making and operational responses.

Adoption level in the EU

The European Union has proactively integrated EO technologies to elevate vessel tracking capabilities. This adoption stems from a need for enhanced security at sea, facilitated through innovative projects like SAGRES and ANISTIAMO.[21] SAGRES, , initiated in January 2013 and ended in December 2014, focused on empowering EU security agencies, including Frontex, with sophisticated EO imagery for better vessel tracking and detection of suspicious activities in European waters. It also concentrated on monitoring departure points for migrant

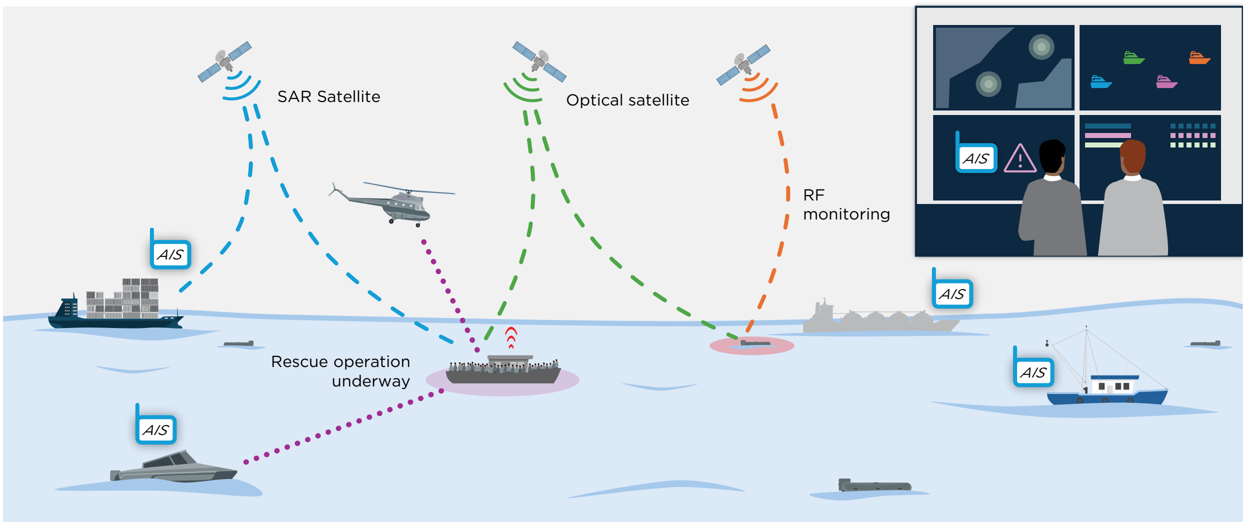

Figure 4. Visual representation of the "Vessel detection and tracking" use case.

[21] https://www.skytek.com/research-and-development/earth-observation/

boats, thus enhancing border control capabilities.[22] This initiative underline the EU's strategic commitment to employing EO technologies for superior maritime security and effective border management, showcasing the seamless integration of satellite data and analytical tools to safeguard European waters.

EO Technologies

- SAR - provides high-resolution imagery regardless of weather or lighting conditions, enabling the identification of vessels attempting to evade detection by disabling AIS signals. This capability allows maritime authorities to maintain continuous surveillance over vast ocean areas, effectively addressing the challenge of "dark vessels" and enhancing overall maritime domain awareness.
- AIS - are an essential component of maritime domain awareness, serving as a collision avoidance and vessel tracking tool. They rely on Very High Frequencies (VHF) transponders on ships to broadcast information such as position, course and speed. These signals can be received by satellites and used to monitor vessel movements, contributing to border management by offering real-time data on maritime traffic. Although AIS provide accurate position data, their effectiveness in illegal vessel detection is limited to those compliant with AIS transmission requirements, necessitating integration with other EO technologies to enhance surveillance and coverage.
- VHR optical imagery - offers unparalleled detail in observing vessels and coastal activities. With spatial resolutions often better than 0.5 meter, VHR satellites capture visible-spectrum images that allow for precise identification of even small objects. This technology complements SAR by providing visual confirmation of detected vessels and enabling advanced analytics, such as automated ship classification. VHR optical imagery is instrumental in augmenting the datasets used for AI-driven analytics, enhancing anomaly detection and activity monitoring.
- HAPS - operate at altitudes typically above 20 km, providing a stationary platform for long-duration observation and monitoring. Their high vantage point allows them to cover extensive maritime areas, bridging the gap between traditional satellites and ground-based and UAV sensors. HAPS can carry a variety of sensors, including optical, infrared and radar, enabling them to perform continuous surveillance and real-time data collection.
- RF sensors – recent advances in satellite technology have significantly enhanced vessel tracking and detection by focusing on the analysis of vessels' RF emissions, thereby improving maritime domain awareness. These emissions, typically in the S- and X-band frequencies and from VHF communications, are detectable by satellites in low-Earth orbit during their brief flyovers, allowing for precise geolocation through angle-of-arrival analysis.
- AI-driven analytics – transform vessel tracking and detection by automatically identifying and classifying vessels and uncovering patterns that could indicate illicit activities.

Gaps and limitations

- Limited AIS integration for "dark vessels" and "spoofing vessels" – one of the most pressing challenges in vessel tracking and detection is dealing with "dark vessels" and "spoofing vessels", which undermine the effectiveness of AIS integration. "Dark vessels" refers to vessels that are not broadcasting their positions due to transponder failures, gaps in signal receiver coverage or intentional deactivation by operators. "Vessel spoofing" involves deliberately manipulating navigation and identification systems like AIS to broadcast false information about a vessel's location, identity or course, thereby compromising the reliability of maritime border surveillance data.[23]
- False positives and data accuracy – a false positive occurs when a system incorrectly identifies something as a vessel when it is not. These errors can lead to wasted resources, as authorities may dispatch patrols to investigate non-existent threats. Ensuring accuracy in vessel detection involves mitigating false positives and refining the precision of satellite geolocation techniques. Advances in machine learning and analytics are essential to improving detection algorithms.

Key applications

- SAR for ship detection – SAR satellites are a cornerstone, since they can pick out ships as bright radar targets on the water day or night. Even a rubber raft or wooden boat will create a return on SAR images if the resolution is sufficient. Large surveillance constellations can now scan key maritime zones several times per day or even per hour, dramatically increasing the chances of catching illegal boats in real time. These systems allow countries to detect and respond to border incursions by sea within hours or minutes, rather than days.

[22] Cordis. "Final Report Summary - SAGRES (Services Activations for GRowing Eurosur's Success)" by Gerard Margarit Martin, December 2015. *https://cordis.europa.eu/project/id/313305/reporting*

[23] Dark Shipping. "Dark Vessel Detection with Satellite-based RF Tracking" by Dark Shipping, 2023. *https://www.darkshipping.com/solutionsexpanded/dark-vessel-detection-with-satellite-based-rf-tracking*

- AIS and data fusion – most commercial ships continuously broadcast AIS signals with their identity and course. Satellite-based AIS reception provides a global plot of legitimate traffic. Border surveillance centres fuse SAR detection data with AIS: any radar-detected vessel that has no corresponding AIS signal is flagged as a "dark vessel" potentially engaged in smuggling or unauthorised entry. This fusion is automated in systems like the EU's Vessel Detection Service, which correlates radar ship detections with ships' self-reported positions to pinpoint suspicious targets.[24] For example, one such scan of the Libyan coast found four unknown vessels where none should be;[25] this alert led to the interception and rescue operation mentioned earlier.
- Vessel tracking and anomaly detection – beyond one-off detection, EO supports long-term tracking of vessel trajectories. Optical and radar satellites can revisit an area to follow a vessel's route, hand off tracking to coastal radar or drones as it nears shore, and even observe it at port (to identify offloading of illegal goods). Analytics software uses EO data to detect anomalies, e.g. a ship slowing in an unusual location (possible rendezvous at sea), or two boats meeting (ship-to-ship transfer) which can indicate transnational smuggling. Frontex's Fusion Service includes "predicting positions and detecting suspicious activities of vessels" using such data-driven methods.[26] If a vessel strays from normal shipping lanes or loiters without explanation, satellites can detect that behaviour and alert authorities.
- Small boat detection – A continuing challenge has been detecting very small craft (like migrant dinghies or narco-speedboats) on open water. These often have low radar reflectivity and can be missed by less sophisticated sensors. However, advances in satellite resolution and processing have improved this. As noted, European services were upgraded to spot smaller vessels. Novel techniques also integrate low-light optical sensors (to see boat lights at night) with radar. For instance, the U.S. has experimented with the VIIRS night-light sensor to pick up the faint lights of boats operating without permission in coastal waters, cross-matching with radar and AIS to expose illegal dark vessels.[27]

SWOT analysis

STRENGTH

Precise vessel tracking, robust data fusion (SAR, AIS)

WEAKNESS

Difficulties detecting small vessels, limited AIS data for dark targets

OPPORTUNITIES

Integration of new AI algorithms, expansion of satellite constellations

THREATS

Cyber threats, evolving countermeasures by illegal vessel operators

[24] Frontex. "Frontex to implement border surveillance services as part of Copernicus" by Frontex, December 2015. https://www.frontex.europa.eu/media-centre/news/news-release/frontex-to-implement-border-surveillance-services-as-part-of-copernicus-Z1r4A0

[25] Alarmphone. "Four shipwrecks in one week off Libya" by Abdel Wahab Latinos, August 2020. https://alarmphone.org/en/2020/08/23/four-shipwrecks-in-one-week-off-libya/

[26] Migrant at sea. "Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats" by Niels Frenzen, October 2015. https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/

[27] SSPI. "How Satellites Secure the Border by SSPI". https://www.sspi.org/cpages/how-satellites-secure-the-border

Case studies

Navigating seas: A satellite-driven initiative for detecting unauthorised vessels – Tuvalu EEZ

In December 2021, Tuvalu Fisheries Department initiated a comprehensive programme to detect unauthorised vessels within the nation's 750 000 km^2 Exclusive Economic Zone. This initiative entailed periodic data collection that varied in timing and coverage, alongside more targeted efforts to support patrol operations by sea and air. The collaborative effort employed both SAR and RF detection methods to evaluate and compare various technologies, and used optical imagery when feasible.

For the project, numerous RF scans as well as 10 SAR acquisitions were conducted, resulting in a total survey area of 25 million km^2. A greater number of RF scans were chosen due to their broader coverage and lower individual acquisition costs compared to SAR. After acquiring the satellite data, the Starboard platform processed it to align detected vessels with known locations and presented the results via a web-based interface. Throughout the programme, roughly 700 vessels were identified using satellite data, most of which could be matched to vessels using AIS and Vessel Monitoring Systems (VMS) transmissions. These matches demonstrated that satellite detections were highly accurate, with RF detections generally within 1 km of a ship's actual location, and SAR detections within 500 meters. Although both types of satellite data may produce false positives and negatives, SAR data rarely missed vessels longer than 30 meters, but could mistakenly identify noise as a vessel. RF scans might fail to detect ships not operating radar or when radar emitters were facing away from the satellite during data collection.[28]

3.3 Coastal and pre-frontier monitoring

Context

"Pre-frontier" monitoring refers to observing areas just outside or approaching a nation's borders – coastal waters before boats land, or neighbouring territories that are launch points for migration or crime. The European Union faces significant challenges in keeping its extensive coastline — over 60 000 kilometres, spanning the Mediterranean, Black and Baltic Seas, and the Atlantic Ocean — safe and secure. With thousands attempting illegal entry by sea annually, and smugglers transporting contraband such as drugs and cigarettes, traditional border patrol methods fall short.[29]

European initiatives like the Copernicus Programme provide high-resolution surveillance through Sentinel satellites equipped with SAR and VHR optical imagery. Additionally, the EU's BorderUAS[30] project integrates UAVs equipped with multi-sensor packages to monitor these areas effectively. HAPS are also being trialled to provide continuous coverage, complementing satellite observations with persistent overhead presence, thus ensuring early detection and timely strategic intervention.

User needs

For effective coastal and pre-frontier monitoring, users require solutions that provide **real-time access to high-resolution satellite data and timely alerts** to enhance response capabilities. **Integrated systems** combining EO imagery with AIS and RF sensor data are essential for comprehensive situational awareness. A **user-friendly interface with intuitive visual displays** supports quick data interpretation and decision-making. Facilitating **cross-border collaboration through secure data sharing** tools enhances cooperation among regions. To ensure uninterrupted surveillance, complementary technologies such as HAPS and UAVs fill coverage gaps.

Adoption level in the EU

The EU has achieved significant progress in adopting EO technologies for coastal and pre-frontier monitoring through several critical initiatives. The Copernicus Programme utilises Sentinel satellites, while EUROSUR facilitates real-time data sharing among Member States, greatly enhancing collective situational awareness and surveillance operations. Innovative projects like BorderUAS integrate UAVs with multi-sensor capabilities to complement satellite observations.

[28] The Central app. "Central business helps with fishing surveillance" by Anna Robb, August 2022. *https://centralapp.nz/NewsStory/central-business-helps-with-fishing-surveillance/62f885330da74c002c19548b*

[29] European Commission. "Eye in the sky boosts EU coastal surveillance" by EC, November 2018. *https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/eye-sky-boosts-eu-coastal-surveillance*

[30] *https://borderuas.eu*

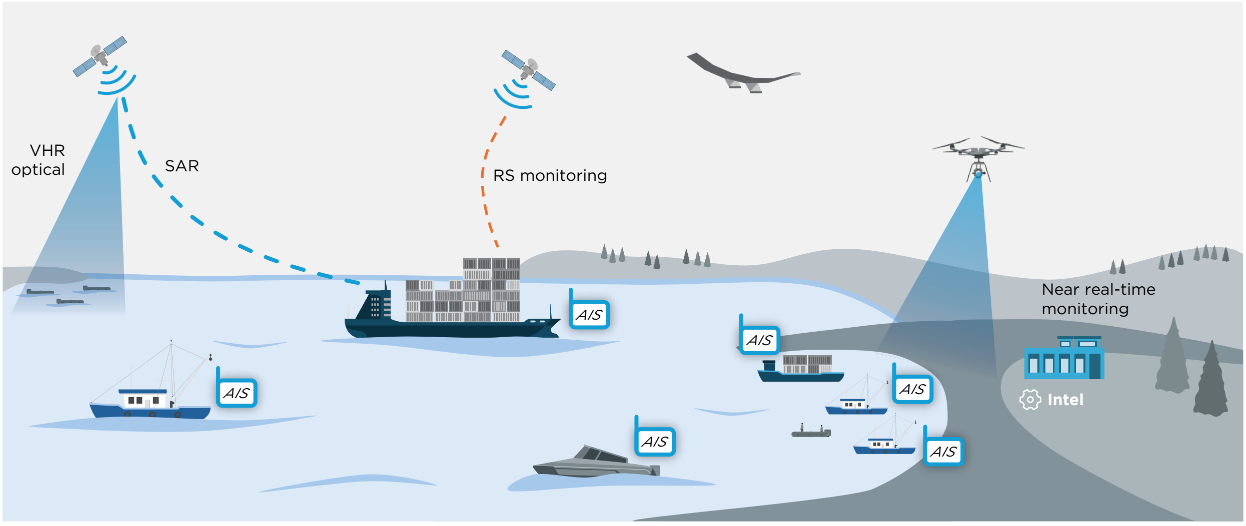

Figure 5. Visual representation of the "Coastal and pre-frontier monitoring" use case.

These efforts underscore the EU's comprehensive and proactive implementation of EO technologies, fundamentally strengthening its border security strategy. Complementing these efforts, the AGAMENON project focuses on enhancing surveillance of migratory routes originating from Africa by leveraging HAPS to monitor vessels and improve coordination between European and African countries, effectively addressing illegal activities and immigration challenges. Together, these initiatives highlight the EU's strategic approach to using EO technologies for robust border management.

EO technologies

- SAR - with resolutions capable of identifying small objects in vast areas, SAR platforms such as Sentinel-1 enable constant surveillance of near-shore waters and adjacent territories, detecting small boats and potential staging activities.
- VHR optical imagery - offers precise visual images, crucial for spotting small boats and identifying potential staging sites such as ports or river deltas.
- AIS - AIS contributes significantly to coastal monitoring by providing real-time data about vessel movements. Satellite-based AIS receivers ensure comprehensive coverage, enabling the identification of legitimate traffic and highlighting "dark vessels" that have deactivated their systems near borders. This is critical for monitoring incoming and outgoing vessels just outside national waters.
- UAVs and HAPS - are increasingly used for coastal and pre-frontier monitoring. These platforms offer flexibility and high-resolution imagery, detecting activities in remote or difficult-to-access regions. They support real-time operations near borders, providing timely intelligence on potential movements of people and goods along unofficial routes.
- RF sensors - detect emissions from navigational and communication systems of vessels near coastal areas, providing insights into activities without the need for direct line-of-sight observation. This technology especially aids in identifying uncooperative vessels attempting to avoid surveillance by disabling AIS, thus enhancing situational awareness along pre-frontier zones.

Gaps and limitations

- Limited predictive capabilities - integrating real-time data from various sources like SAR, optical imagery, RF sensors and AIS is a complex task that demands advanced computational systems to ensure timely and accurate threat detection and response.
- Real-time threat identification - achieving instant threat recognition and response remains complex due to data processing and integration challenges, highlighting the need for continued technological advances.

Key applications

- Coastal zone monitoring - high-resolution satellites monitor coastlines and near-shore waters to spot small boats launching or approaching. For instance, Frontex's Coastal Monitoring service uses frequent optical imagery of North African coasts to detect migrant dinghies preparing to depart for Europe, enabling early intervention. In Asia, satellite images can help identify unauthorised departures of boats carrying migrants or contraband from river deltas and islands. Through surveillance just outside national waters, authorities gain additional response time.

- Staging area surveillance - EO is used to observe border-adjacent regions in other countries that might serve as staging areas for illegal crossings. This includes monitoring migrant camps, as noted earlier, but also watching ports, airstrips, or depots near borders. For example, during Operation Hera off West Africa, EU satellites provided images of beaches in Mauritania showing that migrant boats had launched from there, which officials used as evidence in negotiations.[31] Similarly, if UAV or satellites spot a buildup of trucks near a remote border crossing at night, it could indicate an impending smuggling convoy.
- Environmental indicators of migration - one innovative use of EO is tracking environmental and socioeconomic conditions that can influence migration. The Sentinel satellites measure factors like crop health and drought; a significant crop failure in regions prone to out-migration can signal a coming wave of migrants. Satellites also improve weather forecasting at sea, warning of conditions that might affect migrant boats. This broader "situational awareness" helps border agencies adopt a proactive stance, for example preparing humanitarian corridors if a climate event is likely to displace populations, or increasing patrols if a known conflict region sees new activity visible from space.

SWOT analysis

STRENGTH	WEAKNESS	OPPORTUNITIES	THREATS
Early warning capabilities, proactive threat detection	Dependency on optical sensors and weather conditions	UAV and HAPS deployment, satellite derived DEM usage	Cybersecurity risks, coordinated countermeasures by smugglers

Case studies

Enhancing border security: Europe's strategic use of EO in managing Eastern frontier challenges –

On Europe's eastern frontiers, EO is likewise in play. During the Belarus–EU border crisis in 2021, when thousands of migrants amassed at the Polish borders, commercial satellites provided images of the migrant camps and movements, informing EU Member States and the international community about the scale of the situation. This transparency helped in both diplomatic and operational responses. Moreover, the EUROSUR Fusion Services[32] delivered by Frontex, routinely provide satellite-based "pre-frontier" intelligence to the Member States, covering areas in neighbouring countries used by migrant smugglers. For example, EUROSUR monitored the Balkans route and the Eastern Mediterranean route via regular Sentinel-2 optical imagery and radar, detecting emerging trends such as new gathering points in Turkey and Albania.[33] It is to be noted that fusing satellite data with other news has improved situational awareness and allowed border guards to be deployed more proactively. In summary, case studies show effective multi-agency application of EO – with Frontex as a central hub distributing satellite intelligence to national border forces, yielding concrete operational successes in both migration management and crime interdiction.[34]

[31] Migrant at sea. "Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats" by Niels Frenzen, October 2015. https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/

[32] European Parliament "EUROSUR border surveillance in the pre-frontier area" by European Parliament, June 2021. https://www.europarl.europa.eu/doceo/document/E-9-2021-003295_EN.html

[33] Frontex. "Migratory Routes", by Frontex, 2024. https://www.frontex.europa.eu/what-we-do/monitoring-and-risk-analysis/migratory-routes/migratory-routes/

[34] EUSI. "Border Control in Melilla: A Very High Resolution Look" by European Space Imaging, January 2019. https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/

3.4 Cross-border crime monitoring

Context

The European Union has been challenged by cross-border criminal activities, including drug trafficking, illegal goods smuggling, migrant trafficking and the trade of illegal firearms. In the first half of 2024, Dutch customs intercepted over 16 000 kg of cocaine at seaports.[35] This is further reflected in coordinated EU-wide actions under the European Multidisciplinary Platform Against Criminal Threats (EMPACT) framework in 2023, which led to the identification of 7 500 human trafficking victims and the arrest of 6 801 migrant smugglers.[36] These figures illustrate the complexity and scale of cross-border crimes, showcasing how they are intertwined with international networks and demanding sophisticated monitoring solutions.

EO technologies significantly enhance cross-border crime monitoring by delivering high-resolution, all-weather surveillance capabilities across vast and remote areas. Satellites equipped with SAR and optical imagery provide detailed, real-time data crucial for tracking and detecting illicit activities, such as suspicious vessel movements or unregulated border crossings. By integrating this satellite data with AIS and radio frequency emissions, EO technologies enable comprehensive maritime and terrestrial monitoring.

User needs

To counter cross-border crime, authorities need **real-time situational awareness** that integrates EO data with local intelligence. High-resolution optical, SAR and hyperspectral imagery, combined with AI analytics, enable the detection of smuggling routes, hidden crossings and illicit activities across land and maritime borders. **Predictive analytics** further complement these efforts by analysing patterns and forecasting potential criminal activities, enabling law enforcement agencies to allocate resources strategically and proactively address emerging threats across European borders.

Adoption level in the EU

The EU has achieved a high maturity level in cross-border crime monitoring through comprehensive adoption of EO technologies. For example, Copernicus Border Surveillance initiatives exemplify this by providing satellite-derived information that supports maritime and land-based enforcement actions.[37]

EO Technologies

- Hyperspectral imaging - allows detection of subtle spectral signatures that indicate material compositions, chemical processes or biological states. In the context of cross-border crime monitoring, hyperspectral imaging can identify specific chemical traces associated with illicit activities, such as drug production or illegal crop cultivation (e.g. coca or opium). Despite its limitations in spatial resolution, hyperspectral data provides crucial intelligence for pinpointing locations of criminal operations, enhancing surveillance in regions where covert activities may be conducted.
- VHR optical imagery - is vital for detecting smuggling routes. In maritime contexts, it aids in confirming the presence of illicit vessels and activities by providing comprehensive snapshot assessments.
- SAR - crucial for tracking vessel movements and detecting border breaches across various environments, including rough terrain and maritime regions. Its all-weather capability ensures uninterrupted monitoring.
- Digital Twin - In cross-border crime monitoring, a Digital Twin can integrate EO data to dynamically represent border environments, aiding law enforcement in visualising illegal activities, preparing for breaches and optimising resource allocation through predictive analysis.

Gaps and limitations

- Limited spatial resolution (hyperspectral) - hyperspectral imaging has difficulty achieving the fine detail necessary for detecting small or concealed objects, necessitating other technologies for comprehensive surveillance.
- Difficulty detecting camouflaged objects - despite advanced imaging technologies, covert caches or tunnels still pose detection challenges, underscoring the importance of multi-source data verification.
- Integration challenges with local intelligence - efficient real-time threat identification remains hindered by the complexity of aligning EO data with localised intelligence operations.

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35 NLTimes "Dutch drug seizures fall sharply in first half of 2024; Cocaine total down 42 percent" by NLTimes, July 2024. *https://nltimes.nl/2024/07/09/dutch-drug-seizures-fall-sharply-first-half-2024-cocaine-total-42-percent*

36 European Council. "*Organised crime: Council reports on EU-wide crime-fighting actions*" by Council of the EU, June 2024. *https://www.consilium.europa.eu/en/press/press-releases/2024/06/19/organised-crime-council-reports-on-eu-wide-crime-fighting-actions/*

37 Frontex. "Copernicus programme" by Frontex. *https://www.frontex.europa.eu/what-we-do/copernicus-programme/*

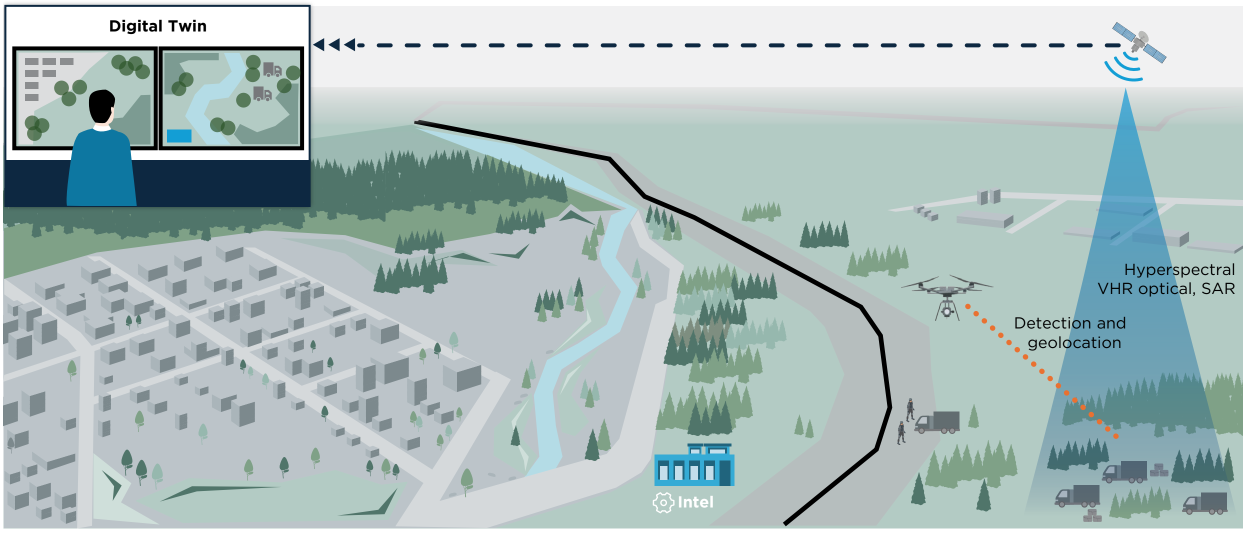

Figure 6. Visual representation of the "Cross-border crime monitoring" use case.

Key applications

- Smuggling route detection (land) - criminal groups often exploit rugged or remote border areas to move contraband. High-resolution satellite images can expose clues of smuggling corridors, like new dirt roads, trails through wilderness or cleared patches near borders that indicate illicit border crossing points. For example, South Africa has used satellite imagery to track activity between its border posts and Zimbabwe – identifying new roads, massed vehicles and breaches in border fences created by smugglers or migrants. Such information allows authorities to reinforce vulnerable border segments or conduct targeted operations.
- Illicit crop and site monitoring - EO is used to detect illegal activities that finance or facilitate crime. Multispectral imagery can detect illicit crop cultivation (e.g. coca, opium) in border regions, while thermal imaging might reveal hidden drug labs or camps due to heat signatures. For instance, hyperspectral data could theoretically identify chemical traces from drug production or unusual materials in conflict zones, providing intelligence on where cross-border criminal networks are operating.
- Maritime smuggling interdiction - many cross-border crime cases involve maritime routes, e.g. narcotics or contraband smuggled via ships. Satellite surveillance of sea lanes has led to significant interdictions. In one Frontex-coordinated operation, satellite radar detected a suspicious vessel in the Mediterranean, and optical imagery helped confirm it as a trafficker's ship, enabling Greek authorities to intercept it and seize 13 tonnes of drugs. Similarly, in 2017, a EU satellite-enabled vessel tracking helped Greece and Spain intercept ships carrying millions of euros in smuggled cigarettes. These examples show how space-based tracking provides a strategic advantage against smugglers who might otherwise evade surface patrols.
- Border conflict and terrorism monitoring - in regions with insurgencies or armed groups, satellite EO is used to monitor border security threats. Governments use reconnaissance satellites to watch disputed borders for troop movements or militant infiltrations. For example, India employs its radar and optical satellites to obtain high-resolution imagery and even video of sensitive border areas, allowing the military to detect incursions in near-real time. Similarly, EO data can reveal the construction of tunnels or fortifications at borders, helping agencies counter terrorism or arms smuggling. (It should be noted that detecting underground tunnels from space is extremely challenging, but repeated imagery might show soil disturbances or infrastructure changes associated with tunnelling.)[38]

[38] Roccheggiani, M.; Piacentini, D.; Tirincanti, E.; Perissin, D.; Menichetti, M. Detection and Monitoring of Tunneling Induced Ground Movements Using Sentinel-1 SAR Interferometry. Remote Sens. 2019, 11, 639. https://doi.org/10.3390/rs11060639

SWOT analysis

STRENGTH

Comprehensive detection capabilities (hyperspectral, optical)

WEAKNESS

Spatial resolution limits, camouflage detection challenges

OPPORTUNITIES

Enhanced sensor modalities (Lidar, hyperspectral), international cooperation

THREATS

Organised crime adaptability, cyber-attacks on EO infrastructure

Case studies

Leveraging satellite data: strengthening the EU's security against cross-border crime.

Surveillance of the EU's external borders relies on advanced Earth Observation technologies to combat cross-border crime. With the aid of the EU's Copernicus Earth Observation Programme, Frontex employs satellite data to enhance its ability to detect irregular migration and maritime crimes, including drug trafficking and migrant smuggling. These criminal activities often use shared routes, necessitating precise tracking and monitoring. Satellite data enables the detection and monitoring of vessels, allowing Frontex and law enforcement to intercept illegal activities. In 2018, operations coordinated by Frontex led to the seizure of 158 tonnes of illegal drugs, illustrating the critical role of satellite data in operational success. Notable operations include Joint Action Day (JAD) Adria in June 2019, which used satellite data to seize nine vessels and 27.4 kg of cannabis, and arrest eight people smugglers. Satellite imagery and data have facilitated the seizure of vessels, leading to significant seizures of contraband and narcotics. These examples highlight the indispensable role of satellite data in enhancing the EU's border security and thwarting illegal cross-border activities.[39,40,41]

3.5 Land border surveillance

Context

Monitoring land borders poses significant challenges due to the expansive and often difficult terrain that must be covered to ensure security and prevent illegal crossings. Traditional surveillance methods struggle to address these challenges comprehensively, particularly in remote or high-traffic areas. EO satellites provide crucial monitoring capabilities, allowing border agencies to spot activity hotspots that may otherwise go unnoticed. By scanning extensive stretches of border terrain, EO technologies help countries identify patterns such as gathering groups or emerging pathways, thus directing limited ground resources to critical areas most effectively. Satellite imagery enables detection of intrusions and physical changes by comparing images over time, helping identify breaches like new gaps in fences, tire tracks or unauthorised structures. Similarly, EO aids in monitoring

[39] Copernicus. "Observer: Copernicus - eyes on the EU's external borders", June 2019. https://www.copernicus.eu/en/observer-copernicus-eyes-on-EU-external-borders

[40] Frontex. "Boat carrying 13 tonnes of drugs intercepted as part of Operation Triton" by Frontex, December 2015. https://www.frontex.europa.eu/media-centre/news/news-release/boat-carrying-13-tonnes-of-drugs-intercepted-as-part-of-operation-triton-QBbcCa

[41] MaritimeFairTrade. "Using Satellite Images To Fight Cross-Border Maritime Crimes" by Lee Kok Leong, September 2019. https://maritimefairtrade.org/using-satellite-images-to-fight-cross-border-maritime-crimes

border infrastructure by mapping surveillance structures to identify areas needing repair or improvement. Furthermore, EO complements ground surveillance systems, integrating with radars and sensors to provide a complete operational picture. This fusion of data allows for quick, informed responses.

User needs

Border security agencies require **precise, real-time data** to effectively manage borders amid growing geopolitical and operational complexities. User needs include wide-area border patrolling to cover hundreds of kilometres efficiently, detection capabilities for intrusions and small-scale changes over time, and comprehensive infrastructure monitoring. **Systems capable of processing large volumes of EO data and integrating seamlessly with existing ground sensors** are crucial for maintaining security and operational efficacy.

Adoption level in the EU

The use of EO technologies for border surveillance in the EU is growing, especially in regions with significant security challenges. Frontex is key in advancing this adoption, supporting the integration of EO data through initiatives like EUROSUR Fusion Services and the Copernicus programme. Projects such as CALLISTO demonstrate the EU's commitment to refining EO capabilities, by using Sentinel-based systems combined with AI and change detection algorithms for precise monitoring and optimised alert systems.[42] Although challenges like limited revisit frequency and integration complexities remain, efforts are underway to enhance border security infrastructure.

To further these advances, Frontex EUROSUR Fusion Services employ EO solutions to address the diverse challenges of monitoring the EU's external borders. Frontex is also promoting the development of innovative solutions through the Copernicus Prize contest, aimed at creating a Digital Twin of land borders to improve the simulation of various events and enhance situational awareness in border management.

EO Technologies

- SAR - using radar pulses, SAR captures wide-area scenes and can detect minute changes in terrain, such as new infrastructure development or patterns of movement along borders. SAR is particularly useful in identifying alterations in soil compaction indicative of recent activity, such as footpaths, or changes in vegetation that may signify human presence or construction efforts. This all-weather capability makes SAR indispensable for continuous monitoring of challenging environments like forests and mountainous regions.
- Optical imagery - provides high-resolution visual data that is crucial for detailed analysis of border areas. This technology is useful for observing static features such as border fences, roads and other infrastructure. Optical imagery allows the identification of changes over time, such as new paths or unauthorised construction, and helps in monitoring the condition and effectiveness of border infrastructure. Despite limitations during

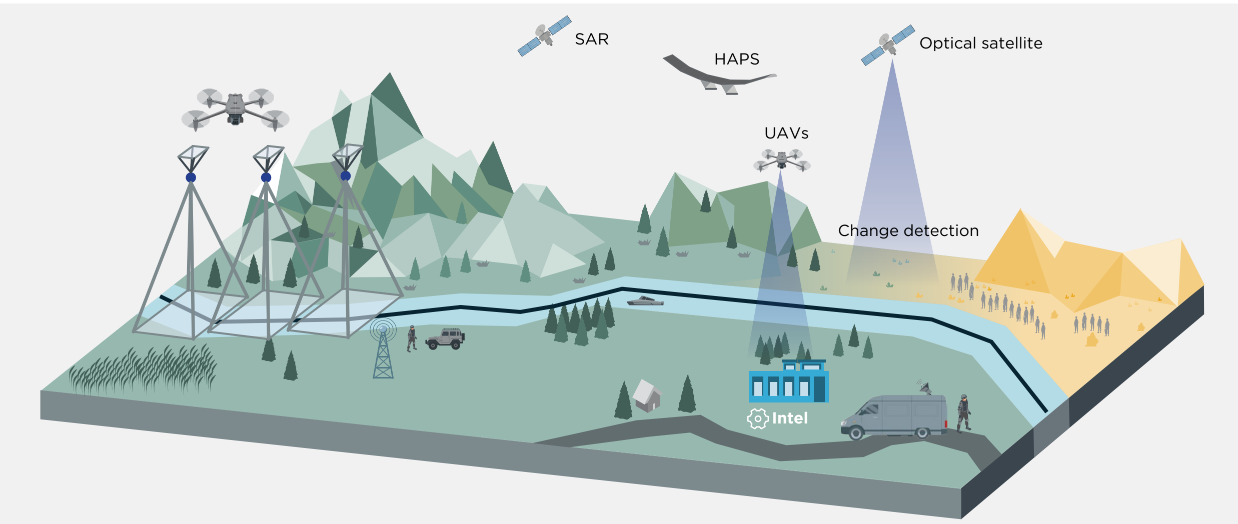

Figure 7. Visual representation of the "Land border surveillance" use case.

[42] https://callisto-h2020.eu/

cloudy periods or nighttime, optical imagery provides invaluable insights when conditions allow.

- UAVs - can conduct targeted surveillance missions in areas that require closer inspection or in scenarios where satellite coverage is less frequent. They are particularly useful for validating alerts generated by satellite imagery and can support live reconnaissance missions to investigate suspicious activities or changes detected from space.
- HAPS - provide persistent coverage of border areas and can fill the gap in temporal monitoring between satellite passes. HAPS platforms support diverse payloads, including optical and infrared sensors, enabling real-time data collection over extended periods. This makes them effective for continuous surveillance and monitoring evolving situations along extensive border sections.
- Change detection algorithms - process EO data to identify deviations over time, whether environmental changes, movement patterns or infrastructure developments. These algorithms analyse consecutive datasets from SAR or optical imagery to pinpoint changes that may indicate unauthorised activities. They are vital for maintaining a dynamic surveillance approach, allowing border agencies to adjust resources and respond promptly to emerging threats or breaches.

Gaps and limitations

- Limited revisit frequency - satellites, especially those in polar orbits, may not pass over the same area frequently enough to catch rapidly changing events, potentially leading to delays in detecting illicit activities or environmental changes.
- Integration of satellite data with ground sensor data - there are significant technical and operational challenges in integrating satellite data with ground sensor networks, such as RF sensors and Signal Intelligence (SIGINT) systems, which can complicate data fusion and interpretation, leading to potential gaps in coverage or response.
- Challenges in accurately identifying small-scale changes - detecting minor alterations, such as individual footprints or small-scale tunnelling activity - can be challenging and may require complementary technologies like UAVs for detailed inspection, thus complicating the surveillance setup.

Key applications

- Wide-area border patrolling – EO satellites give a top-down view of the entire border region, helping identify hotspots of activities that might be otherwise overlooked. Instead of only monitoring known crossing points, border agencies use EO to periodically scan hundreds of kilometres of border terrain. The U.S. Department of Homeland Security (DHS), for example, has shared reconnaissance satellite imagery with Border Patrol to watch high-traffic points where illegal crossings peak. These images can reveal patterns such as groups gathering on the Mexican side or footpaths forming in remote sectors. India similarly captures frequent satellite images along disputed or porous borders to keep constant watch over broad areas. This kind of visibility helps direct limited ground resources to where they're most needed. CBSS uses EO data to offer border authorities crucial information for enhanced situational awareness and improved reaction capabilities.
- Detection of intrusions and changes - By comparing images over time, analysts can detect physical changes or movements along the border. A prime technique is using SAR or optical imagery for change detection: if a new gap appears in a border fence, new tire tracks cross a barren area or a makeshift bridge or tunnel entrance pops up, multi-temporal satellite analysis will flag it.[43] U.S. Customs and Border Protection (CBP) has employed an airborne SAR called VADER[44] to do exactly this – digitally comparing radar scans to spot human footprints or vehicle tracks in the desert. The same concept extends to satellite SAR data. Even if satellites pass less frequently than drones, they can capture before/after snapshots of remote border stretches to reveal where an illicit crossing likely occurred (prompting agents to investigate on the ground). Frontex employs satellite data, including SAR, to monitor the EU's external borders, detecting unauthorised crossings and infrastructure changes in remote areas by detecting people both in visible light and hidden behind opaque layers (like foliage, trailer covers or boat covers), or in darkness and reduced visibility conditions.[45]
- Monitoring border infrastructure - EO also aids in maintaining and evaluating border infrastructure. High-resolution images are used to map border fences, walls and surveillance towers, identifying sections that might be damaged or bypassed. For instance, 30 cm resolution satellite imagery over the Spain-Morocco

[43] CATO Institute. "Drones on the Border: Efficacy and Privacy Implications" by David J.Bier and Matthew Feeney, May 2018. https://www.cato.org/immigration-research-policy-brief/drones-border-efficacy-privacy-implications

[44] Defense Daily. "CBP Wants Six VaDER Radar For Border Security Operations" by Calvin Biesecker, October 2013. https://www.defensedaily.com/cbpwants-six-vaderradar-for-border-security-operations/homeland-security/

[45] Statewatch. "Seeing through trees: Frontex commissions study on solutions for under-foliage detection" by Statewatch, February 2014. https://www.statewatch.org/news/2014/february/seeing-through-trees-frontex-commissions-study-on-solutions-for-under-foliage-detection/

border at Melilla has been able to show every detail of the multi-layered fence defences.[46] This helps authorities study the effectiveness of barriers and see where improvements or repairs are needed. It also provides evidence in case of disputes (e.g. if a neighbouring country is suspected of tampering with border markers or if new construction approaches the border line).

- Augmenting ground surveillance systems - Data from EO can be integrated with ground sensor networks. Border security often uses ground-based radars, seismic sensors and camera towers. Satellites complement these systems by covering blind spots – for example, if a ground-based radar detects movement, and a satellite image can determine whether it is human activity or just natural phenomena such as wildlife. Conversely, if satellite monitoring shows a group of people close to the borders, border guards can be warned to be vigilant in that sector. Modern border command centres fuse satellite imagery, UAVs feeds and ground sensor data into a common operational picture. One U.S. DHS programme is developing automated tools to process satellite imagery and alert border agents of likely "nefarious activities," so they can respond faster.[47]

SWOT analysis

STRENGTH	WEAKNESS	OPPORTUNITIES	THREATS
Broad area coverage, effective change detection algorithms	Limited revisit intervals, challenges in integration with ground data	Increased satellite revisit frequency, deployment of drones	Cyber vulnerabilities, sabotage of border infrastructure

Case studies

Integrating sky and space: The evolving role of EO in securing the U.S. southern border

The United States employs a mix of satellites, aerial assets, and ground sensors to secure its extensive southern border. While the U.S. has military-grade spy satellites, much of their data remains classified; however, DHS has increasingly tapped into EO capabilities for civilian border security. One notable project is the Adaptive Sensor Analytics Project (ASAP) of the Science and Technology Directorate supporting the Department of Homeland Security (DHS), which anticipates the proliferation of commercial imaging satellites.

As early as 2017, DHS recognised that in "five to ten years, commercial imagery constellations" will be able to rapidly image border regions, providing much more frequent coverage.[48] To not be overwhelmed by this data, DHS started developing AI analytics to automatically process satellite imagery and flag patterns of illegal crossings or smuggling activities. This forward-leaning approach is now bearing fruit as multiple private companies can supply daily imagery of the border.

[46] EUSI. "Border Control in Melilla: A Very High Resolution Look" by European Space Imaging, January 2019. https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/

[47] Department of Homeland Security. "Snapshot: Using Satellites and Data Analytics to Protect the Homeland" by DHS, September 2017. https://www.dhs.gov/archive/science-and-technology/news/2017/09/29/snapshot-using-satellites-and-data-analytics-protect-homeland

[48] Department of Homeland Security. "Snapshot: Using Satellites and Data Analytics to Protect the Homeland" by DHS, September 2017. https://www.dhs.gov/archive/science-and-technology/news/2017/09/29/snapshot-using-satellites-and-data-analytics-protect-homeland

In operational terms, the U.S. has so far relied more on aerial surveillance but with satellite support. Customs and Border Protection (CBP) Predator-B UAVs patrol large stretches of the border and are equipped with EO/IR cameras and Synthetic Aperture Radar. Two UAVs in Arizona carry the VADER SAR, which, as mentioned, can track moving “dismounts” (people on foot) and vehicles by detecting movement and comparing snapshots over time. This capability has led to detections of smugglers walking drugs across remote desert areas that agents would have likely missed otherwise.

In one documented case, a Predator UAV tracked a group crossing the border and was ready to guide agents, but unfortunately cloud cover intervened, illustrating the limits of electro-optical sensors and the need for radar or satellite overwatch when UAVs are blinded. The U.S. has also trialled the use of small satellites for border monitoring. For instance, reports indicate that CBP has accessed imagery from commercial satellites to monitor the Rio Grande region for raft crossings and to scope out cartel lookout positions on Mexican hilltops. While specific case outcomes are not widely publicised, GAO reports and CBP statements suggest that a fraction of drug seizures and migrant apprehensions each year have been attributed to aerial/satellite surveillance cues (though the Cato Institute has critiqued the efficiency of the large UAV programme). Looking forward, the U.S. is exploring high-altitude balloons and stratospheric UAVs (HAPS) to persistently watch border areas from 60,000 feet, effectively functioning like pseudo-satellites. One recent pilot involved a balloon over the southern border that stayed aloft for weeks, imaging and intercepting communications – showcasing another facet of “EO” technology deployment.

In summary, the U.S. case underscores that EO contributions to land border security are growing. From automated satellite image analysis to radar-equipped UAVs, these tools have enhanced detection of illicit border activity. The key lesson has been the importance of integration: satellites provide broad coverage and strategic warning, while UAVs and ground units do the tactical interdiction. With the rapid expansion of commercial EO data (and projects like a planned constellation of U.S. surveillance satellites dedicated to DHS), the U.S.–Mexico border is likely to see even greater use of space assets in the near future, filling gaps in the current surveillance network.

3.6 Irregular migration monitoring

Context

Irregular migration poses a major challenge for border authorities, as it often takes place in remote or hard-to-reach areas where gathering accurate information is difficult. According to the International Organization for Migration, irregular migration refers to movements that fall outside traditional patterns, often with the goal of evading detection. As migrants’ circumstances and statuses change, tracking their movements becomes even more complex, making it a significant hurdle for effective border management.[49] Consequently, understanding of the levels and dynamics of irregular migration remains limited, especially on the global scale. Existing datasets in the EU offer some insight into aspects such as attempted irregular crossings, detected irregular stays and loss of regular status, yet these data sources are often incomplete and inconsistent, failing to capture the full complexity of irregular migration and return processes.

EO technologies can significantly enhance monitoring efforts by providing comprehensive, real-time insights into migration activities across vast and challenging terrains. Satellites equipped with optical and radar sensors offer top-down views that can help identify movement patterns and hotspots that might be missed by ground-based detection systems. EO data allows border agencies to detect and monitor these activities more effectively, providing critical strategic and operational insights into migration trends. By integrating EO data with existing datasets, authorities can address inconsistencies and improve their understanding of irregular migration dynamics, enhancing border security and response capabilities.

User needs

The key users of EO-based migration monitoring systems are government agencies, humanitarian organisations and researchers. Border control authorities, immigration services, and security agencies require **real-time information** to manage migration flows, anticipate surges, and prevent illegal crossings. NGOs and international aid agencies need to **assess the scale of migration crises, locate migrants in need and optimise aid distribution.** Academics and analysts use EO data to study migration patterns, understand the factors driving migration and assess the effectiveness of policy interventions.

49 Migration data portal. “Irregular migration” by MDP, September 2022. *https://www.migrationdataportal.org/themes/irregular-migration*

Adoption level in the EU

The EU is at the forefront of using EO for migration monitoring, driven by the significant influx of migrants in recent years. Frontex employs EO data, including AIS and SAR, to detect migrant boats in the Mediterranean Sea. There are several research projects using EO data to map refugee camps, track migration routes, and assess the impact of migration on the environment. In addition, those initiatives contribute by measuring environmental and socioeconomic factors, such as crop health and drought, which can influence migration patterns.[50] These data support proactive border management strategies, including preparing a humanitarian response to anticipated migration waves due to environmental stressors. UNOSAT, a UN entity, uses EO data to map refugee camps, identify potential migration routes, and support humanitarian response efforts.[51] These initiatives demonstrate the growing recognition of EO's potential in providing valuable insights for managing irregular migration and responding to humanitarian crises.

EO Technologies

- AIS - provides real-time data on vessels equipped with AIS transponders, aiding in tracking maritime traffic and identifying potential migrant boats.
- SAR - provides insights into changes in land use, revealing new foot trails, tire tracks and other indicators of human movement. What is more, change detection algorithms using SAR can highlight areas where groups have traversed open land at night, providing evidence of border crossings.
- VHR optical imagery - used to create detailed maps of refugee camps, identify new migrant settlements, and estimate the number of migrants in an area. It also helps locate hidden migrant camps near borders, allowing for early detection and response. Furthermore, VHR optical satellites provide essential data for calculating environmental indices such as NDVI, SAVI, EVI, and NDWI, which are used to analyse vegetation health, soil moisture, and water availability. By analysing these indices, authorities can better predict areas at risk of drought and other environmental stresses that may trigger or increase irregular migration.
- UAVs - offer high-resolution real-time surveillance at specific locations, aiding in the monitoring of land and sea movements.
- HAPS - provide persistent coverage over specific areas, offering a cost-effective alternative to satellites for certain monitoring tasks.

Gaps and limitations

- Limited revisit and real-time response capabilities - EO satellites often have limited revisit times, meaning they cannot continuously monitor specific areas.
- Reliance on supplementary ground intelligence - while EO provides valuable overhead data, it is frequently insufficient on its own. Effective irregular migration monitoring often requires integration with ground intelligence, such as reports from border patrols and IoT sensors.
- Difficulties in detecting very small boats - EO technologies, particularly those with lower resolution, can struggle to detect and monitor very small boats frequently used in irregular migration. These vessels may easily blend into the surrounding sea or evade detection due to their size, particularly in challenging weather or sea conditions.

Key applications

- Small vessel tracking - As noted above, satellite imaging and AIS are used in the Mediterranean, Aegean and other seas to spot migrant boats. Frontex's system, for instance, scans wide areas with SAR and tasks VHR optical satellites to identify and track boats, even small inflatable rafts.[52] This has been effective in guiding naval assets to boats in need and documenting the scale of migration. Recent upgrades to European EO services "make it possible to spot smaller vessels" that previously eluded detection[53] – a critical improvement for catching human traffickers' boats or tiny dinghies carrying migrants.
- Mapping land migration routes and camps - EO is also used to monitor overland migration corridors and temporary camps before migrants reach a border. Satellite radar and imaging have been used to gauge the size of refugee camps on the edges of Europe. By observing growth or movements in these camps, authorities can anticipate surges in migration and prepare humanitarian or security responses. This "pre-frontier" intelligence helps balance border security with migrant protection – for example, identifying

[50] European Space Agency. "On the move" by ESA. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Space_for_Sustainable_Development/On_the_move

[51] UNOSAT. "Syrian Refugee Camps" by UNOSAT, March 2012. https://unosat.org/products/633

[52] Via Satellite. "People Watching: Tracking and Monitoring Migration" by Joanne Wheeler, July 24th, 2023, Via Satellite Magazine. https://interactive.satellitetoday.com/via/articles/people-watching-tracking-and-monitoring-migration

[53] Migrant at sea. "Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats" by Niels Frenzen, October 2015. https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/

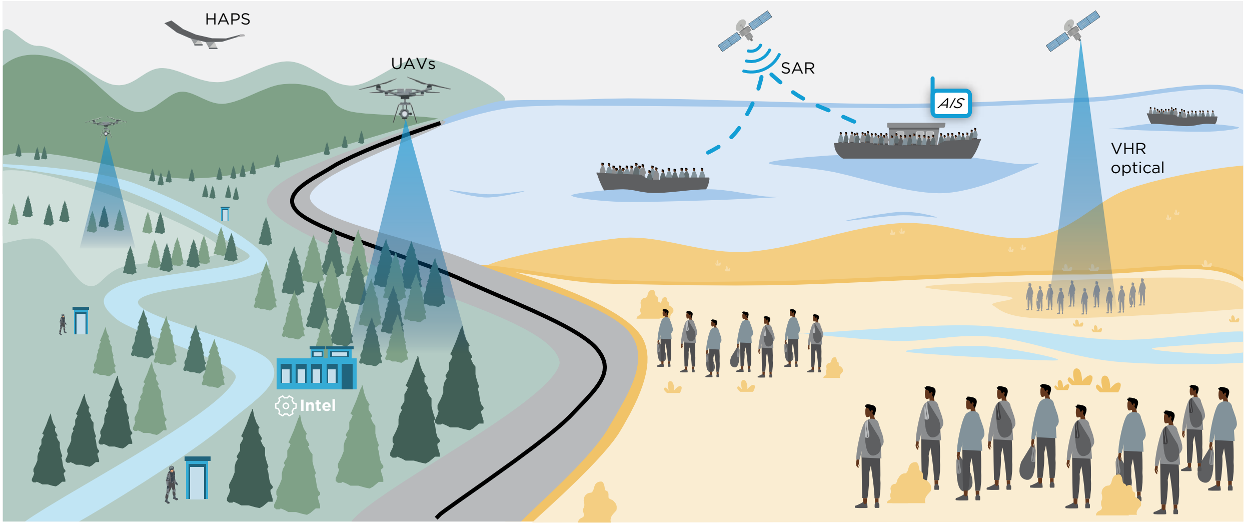

Figure 8. Visual representation of the "Irregular migration monitoring" use case.

where people mass so that safe routes or aid can be arranged, and potentially deterring migrants from taking especially perilous paths.

- Remote border crossing - In regions like the U.S.–Mexico border or the southern border of the EU, irregular migrants often travel through difficult, roadless terrain such as steep mountains or dense forests. EO data (satellite or UAV-based) can reveal signs of these movements – e.g. new foot trails or tire tracks appearing in imagery. Change-detection algorithms using SAR can highlight where groups might have traversed open land at night (by comparing radar images before/after to catch disturbances). While individual people are often too small to directly identify from satellites, the indicators of their movement (paths, disturbed vegetation, campsites etc.) can be detected and monitored. For instance, analysts have used VHR imagery to locate hidden encampments of migrants preparing to cross (such as in the hills near Melilla, Spain),[54] enabling border guards to better focus patrols and even deliver aid or warnings.

SWOT analysis

STRENGTH	WEAKNESS	OPPORTUNITIES	THREATS
Effective boat and camp monitoring capabilities	Real-time detection limitations, reliance on ground intel	Enhanced AI-driven analytics, integration of multi-sensor platforms	Adaptation by traffickers, misinformation campaigns affecting operations

Case studies

Since 2014, Venezuela has experienced a severe socio-economic crisis, resulting in the displacement of millions of its citizens. Nearly 2 million Venezuelan migrants have crossed into Colombia, many of whom settled in informal and often undocumented settlements. This posed significant challenges for humanitarian agencies

[54] EUSI. "Border Control in Melilla: A Very High Resolution Look" by European Space Imaging, January 2019. https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/

trying to provide aid and support, as these settlements were typically unregistered, rapidly evolving and located in remote areas.

To address this, researchers developed a cost-effective, scalable method to monitor the emergence of these settlements using satellite data and machine learning. Researchers used time-series imagery from the Sentinel-2 satellites, covering Colombian regions from 2015 to 2020. By applying machine learning algorithms to detect changes in land use and settlement patterns, the system was able to identify new informal housing clusters.

This integrated approach enabled the identification of previously undocumented informal settlements, which in turn allowed NGOs and local authorities to better allocate humanitarian resources and respond more effectively to migrant needs. This method not only proved successful in the Colombian context but also demonstrated potential for replication in other regions facing migration-induced settlement growth.[55]

4. Challenges in Earth Observation-based Border Management

Figure 9. Challenges in EO-based border management.

While EO has proven invaluable, there are still notable challenges and limitations when using these technologies in border security.

Coverage vs. persistence

Satellites provide wide coverage, but with current constellations are not continuously over any given point. A border area might be imaged once a day or even less frequently. Critical events can be missed during the gaps. A migrant group might cross between satellite passes; a smuggler might exploit known satellite schedules. Increasing satellite revisit rates (through larger constellations or complementary airborne UAVs) is one solution, but managing a truly persistent state over a border is difficult and costly. High-altitude platform

[55] Tingzon, I., Dejito, N., Flores, R. A., De Guzman, R., Carvajal, L., Erazo, K. Z., ... & Ghani, R. (2020). Mapping New Informal Settlements using Machine Learning and Time Series Satellite Images: An Application in the Venezuelan Migration Crisis.

systems (HAPS) are being explored to fill this need by loitering over key areas,[56] but these are still in the testing phase. The goal is "persistent surveillance," yet achieving it requires a network of sensors and remains a challenge over thousands of kilometres of border.

Weather and lighting constraints

Traditional optical satellites are hampered by cloud cover, fog/haze, snow and night darkness.[57] While SAR solves this to some extent, SAR images can be harder to interpret for certain targets (e.g. people or small vehicles amidst clutter) and may require specialist analysis. Likewise, detecting human activity under forest canopy or dense vegetation is a major challenge – neither optical nor current space-based radar (mostly X-band/C-band) can see through dense foliage. Research into foliage-penetration radar (like P-band SAR) or using hyperspectral signals to catch subtle changes is ongoing,[58] but not yet an operational solution. In essence, harsh weather or thick cloud/vegetation cover can still provide adversaries places to hide from EO surveillance.

Resolution and identification limits

Even the sharpest commercial imaging satellites (~30 cm resolution) have intrinsic limits: they can detect the presence of a person or a vehicle but cannot positively support an identification process. Similarly, satellites might spot a pickup truck crossing a border in rough terrain, but they might not determine what's inside it (drugs or legal cargo?). There are specialised sensors (e.g. hyperspectral could hint at drug chemicals, or thermal could show warm bodies in a vehicle at night), but these are not widely deployed from space. This limitation necessitates fusion with human intelligence and ground operations – EO by itself is rarely a silver bullet to close a case.

Data overload and analysis bottlenecks

The expanding volume of EO data presents a challenge in analysis. Border agencies can task many satellites and drones, yielding terabytes of imagery and signals. Sifting this manually for actionable insights is labour-intensive and can be slow – "speed of data" can far exceed the "speed of humans" in analysis. This lag can make surveillance less effective (e.g. by the time analysts flag an illegal crossing in imagery, the perpetrators may be long gone). To mitigate this, investments in automation, AI and big data processing are crucial. DHS's analytics project and Frontex's development of cloud-based big data platforms for satellite information are responses to this challenge. The technology is improving, but ensuring analysts aren't overwhelmed – and that critical alerts aren't lost in the noise – remains an ongoing effort.

Integration and interoperability

Border security involves multiple systems (ground radars, cameras, satellites, databases). Integrating EO data with other systems in real time is complex. Different data formats and update rates, and the need for secure, fast

[56] European Commission. "Weak Signals in Border Management and Surveillance Technologies" by Olivier Eulaerts and Geraldine Joanny, June 2022 https://publications.jrc.ec.europa.eu/repository/handle/JRC128871

[57] Quick Signal. "Mitigating Risk with Advanced Surveillance Technologies" by Quickset, May 2024. https://www.quickset.com/mitigating-risk-with-advanced-surveillance-technologies/

[58] Schreiber, D.; Opitz, A. A Novel Background Modelling Algorithm for Hyperspectral Ground-Based Surveillance and Through-Foliage Detection. 2022

communications links, can cause friction. For example, streaming UAV video into the same command system as satellite imagery and AIS feeds requires robust network infrastructure. Some countries or agencies may lag in infrastructure, leading to underuse of available EO data. Additionally, data sharing between the EU Member States about the EU external border zones can face legal/political hurdles.

Countermeasures by adversaries

Just as border agencies are adopting EO, those trying to breach borders are adapting. Smugglers and migrants may use camouflage tarps to try to hide from aerial view, travel during cloud cover or new moon nights (to evade both optical and night-light detection), or use decoys to confuse automated detection. There have been instances of drug traffickers learning UAV routes and timing, then moving just outside those windows. In the cyber realm, in one case drug cartels even hacked U.S. UAVs' Global Navigation Satellite System (GNSS) to throw them off course. While satellites are harder to interfere with, adversaries can still attempt AIS spoofing (broadcasting false ship identities) or simply switch off devices. Thus, EO systems face a cat-and-mouse dynamic: as capabilities improve, so do counter-tactics. Border agencies must be aware of these and continue innovating (e.g. using unpredictable satellite scheduling, deploying radar that can't be easily spoofed, etc.).

Cost and accessibility

High-quality EO data and infrastructure can be expensive. Not all countries can afford their own satellites or constant commercial imagery purchases. While programmes like Copernicus provide a lot of free data (Sentinel satellites) and collective services, some advanced needs (e.g. 30 cm imagery or hourly revisit radar) still cost significant funds. There's a risk that less-developed nations with critical border issues might be left behind in using EO. International support and cost-sharing (as the EU does for its Member States) is a model to mitigate this. Also, as smallsat constellations drive prices down, this challenge is gradually easing, but budgeting for EO in border agencies – including the analysts and systems to use it – is an ongoing consideration.

Privacy and ethical concerns

Though less discussed in security contexts, pervasive surveillance, including space-based EO, raises privacy concerns. Continuous border monitoring can incidentally capture civilian activities, raising the risk of misuse and tracking of vulnerable groups. While regulations like the General Data Protection Regulation (GDPR) and the EU AI Act aim to address these concerns within the European Union, the balance between security and privacy remains a complex challenge. Border agencies must ensure that EO data, including satellite imagery, is used solely for its intended law enforcement purpose and not for indiscriminate surveillance, respecting individual fundamental rights. Furthermore, humanitarian considerations necessitate using EO for life-saving purposes, such as directing rescue efforts for migrants in distress, not solely for border enforcement. This delicate balancing act requires continuous dialogue and adaptation of both policy and technology.

In essence, while EO offers significant advancements in border security, it's crucial to acknowledge its inherent limitations. Technical constraints like revisit rates, weather interference and resolution limitations, along with operational hurdles related to data volume and system integration, impact its effectiveness. Furthermore, adaptive adversaries constantly evolve their tactics, requiring continuous adaptation of EO-based security measures. While EO's origins are rooted in security and military applications, recognising these ongoing challenges is essential to avoid over-reliance and drive future improvements.

References

[1] Maxar. "Clarity and confidence" by Maxar, 2025. *https://go.maxar.com/Imagery-Leadership-Spatial-Resolution*

[2] Satellite Imaging Corporation. "Satellite Imaging Corporation. Sentinel-2A Satellite Sensor (10m)" by Satellite Imaging Corporation. *https://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/sentinel-2a/*

[3] NASA Landsat Science. "Landsat 8" by NASA. *https://landsat.gsfc.nasa.gov/satellites/landsat-8/*

[4] pixxel. "Hyperspectral imagery" by pixxel. *https://www.pixxel.space/hyperspectral-imagery*

[5] eoPortal. "Hyperspectral Imaging" by Herbert J. Kramer, August 2023. *https://www.eoportal.org/other-space-activities/hyperspectral-imaging#references*

[6] Jou-Claus, S., Folch, A., and Garcia-Orellana, J.: Applicability of Landsat 8 thermal infrared sensor for identifying submarine groundwater discharge springs in the Mediterranean Sea basin, Hydrol. Earth Syst. Sci., 25, 4789–4805, *https://doi.org/10.5194/hess-25-4789-2021, 2021.*

[7] International Maritime Organisation. "Revised guidelines for the onboard operational use of shipborne automatic identification systems (AIS)." Resolution A.1106(29), 2015. *https://www.classnk.or.jp/hp/pdf/activities/statutory/ism/imo/imo_a1106-29.pdf*

[8] EUSI. "What is SAR Imagery? Introduction to Synthetic Aperture Radar", 2024. *https://www.euspaceimaging.com/blog/2024/04/05/what-is-sar-imagery/*

[9] Rhode&Schwarz. "Securing borders, safeguarding futures: The critical role of RF sensors" by Rhode&Schwarz. *https://www.rohde-schwarz.com/solutions/aerospace-and-defense/multi-domain/border-security/border-security_258207.html?change_c=true*

[10] GEONADIR. "What is the resolution of drone mapping?" by Dr Karen Joyce February 2022. *https://geonadir.com/drone-resolution/*

[11] ESA. "Sentinel-1 - Radar vision for Copernicus" by ESA. *https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1*

[12] *https://www.iceye.com/*

[13] Government of Canada. "Radarsat-2" by Government of Canada, December 2023. *https://www.asc-csa.gc.ca/eng/satellites/radarsat2/*

[14] *https://www.he360.com/*

[15] *https://kleos.space/*

[16] UBOTICA. "Illuminating the Invisible: How Ubotica is Revolutionising Dark Vessel Detection" by Barry Nolan March 2025. *https://ubotica.com/illuminating-the-invisible-how-ubotica-is-revolutionising-dark-vessel-detection/*

[17] EMSA. "Discover the EU Maritime Profile" by EMSA. *https://www.emsa.europa.eu/eumaritimeprofile.html*

[18] SSPI. "How Satellites Secure the Border" by SSPI. *https://www.sspi.org/cpages/how-satellites-secure-the-border*

[19] EDA. Maritime Surveillance (MARSUR) by EDA. *https://eda.europa.eu/what-we-do/all-activities/activities-search/maritime-surveillance-(marsur)*

[20] EDA. Maritime Surveillance (MARSUR) by EDA. *https://eda.europa.eu/what-we-do/all-activities/activities-search/maritime-surveillance-(marsur)*

[21] EMSA. Surveillance by EMSA. *https://www.emsa.europa.eu/we-do/surveillance.html*

[22] EDA. Maritime Surveillance (MARSUR) by EDA. *https://eda.europa.eu/what-we-do/all-activities/activities-search/maritime-surveillance-(marsur)*

[23] EDA. Maritime Surveillance (MARSUR) by EDA. *https://eda.europa.eu/what-we-do/all-activities/activities-search/maritime-surveillance-(marsur)*

[24] MaritimeFairTrade. "Using Satellite Images To Fight Cross-Border Maritime Crimes" by Lee Kok Leong, September 2019. *https://maritimefairtrade.org/using-satellite-images-to-fight-cross-border-maritime-crimes*

[25] Copernicus. "Observer: Copernicus - eyes on the EU's external borders", June 2019. *https://www.copernicus.eu/en/observer-copernicus-eyes-on-EU-external-borders*

[26] Frontex. "Boat carrying 13 tonnes of drugs intercepted as part of Operation Triton" by Frontex, December 2015. *https://www.frontex.europa.eu/media-centre/news/news-release/boat-carrying-13-tonnes-of-drugs-intercepted-as-part-of-operation-triton-QBbcCa*

[27] MaritimeFairTrade. "Using Satellite Images To Fight Cross-Border Maritime Crimes" by Lee Kok Leong, September 2019. *https://maritimefairtrade.org/using-satellite-images-to-fight-cross-border-maritime-crimes/*

[28] EUSI. "Border Control in Melilla: A Very High Resolution Look" by European Space Imaging, January 2019. *https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/*

[29] *https://www.skytek.com/research-and-development/earth-observation/*

[30] Cordis. "Final Report Summary - SAGRES (Services Activations for GRowing Eurosur's Success)" by Gerard Margarit Martin, December 2015. *https://cordis.europa.eu/project/id/313305/reporting*
[31] *https://www.skytek.com/research-and-development/earth-observation/*
[32] Dark Shipping. "Dark Vessel Detection with Satellite-based RF Tracking" by Dark Shipping, 2023. *https://www.darkshipping.com/solutionsexpanded/dark-vessel-detection-with-satellite-based-rf-tracking*
[33] Frontex. "Frontex to implement border surveillance services as part of Copernicus" by Frontex, December 2015. *https://www.frontex.europa.eu/media-centre/news/news-release/frontex-to-implement-border-surveillance-services-as-part-of-copernicus-Z1r4A0*
[34] Alarmphone. "Four shipwrecks in one week off Libya" by Abdel Wahab Latinos, August 2020. *https://alarmphone.org/en/2020/08/23/four-shipwrecks-in-one-week-off-libya/*
[35] Migrant at sea. "Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats" by Niels Frenzen, October 2015. *https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/*
[36] SSPI. "How Satellites Secure the Border by SSPI". *https://www.sspi.org/cpages/how-satellites-secure-the-border*
[37] The Central app. "Central business helps with fishing surveillance" by Anna Robb, August 2022. *https://centralapp.nz/NewsStory/central-business-helps-with-fishing-surveillance/62f885330da74c002c19548b*
[38] European Commission. "Eye in the sky boosts EU coastal surveillance" by EC, November 2018. *https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/eye-sky-boosts-eu-coastal-surveillance*
[39] *https://earth.esa.int/eogateway/missions/radarsat*
[40] *https://www.maxar.com/maxar-intelligence/constellation*
[41] *https://borderuas.eu/*
[42] Migration and Home Affairs. Eurosur. *https://home-affairs.ec.europa.eu/policies/schengen/old-border-crossing/eurosur_en*
[43] EMSA. "Copernicus Maritime Surveillance Service" by EMSA. *https://www.emsa.europa.eu/copernicus.html*
[44] Migrant at sea. "Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats" by Niels Frenzen, October 2015. *https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/*
[45] Migrant at sea. "Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats" by Niels Frenzen, October 2015. *https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/*
[46] European Parliament "EUROSUR border surveillance in the pre-frontier area" by European Parliament, June 2021. *https://www.europarl.europa.eu/doceo/document/E-9-2021-003295_EN.html*
[47] Frontex. "Migratory Routes", by Frontex, 2024. *https://www.frontex.europa.eu/what-we-do/monitoring-and-risk-analysis/migratory-routes/migratory-routes/*
[48] EUSI. "Border Control in Melilla: A Very High Resolution Look" by European Space Imaging, January 2019. *https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/*
[49] NLTimes "Dutch drug seizures fall sharply in first half of 2024; Cocaine total down 42 percent" by NLTimes, July 2024. *https://nltimes.nl/2024/07/09/dutch-drug-seizures-fall-sharply-first-half-2024-cocaine-total-42-percent*
[50] European Council. "Organised crime: Council reports on EU-wide crime-fighting actions" by Council of the EU, June 2024. *https://www.consilium.europa.eu/en/press/press-releases/2024/06/19/organised-crime-council-reports-on-eu-wide-crime-fighting-actions/*
[51] Frontex. "Copernicus programme" by Frontex. *https://www.frontex.europa.eu/what-we-do/copernicus-programme/*
[52] eoPortal. "RISAT-1 (Radar Imaging Satellite-1) by eoPortal. *https://www.eoportal.org/satellite-missions/risat-1*
[53] ISRO. "Cartosat-1" by ISRO. *https://www.isro.gov.in/CARTOSAT_1.html*
[54] Roccheggiani, M.; Piacentini, D.; Tirincanti, E.; Perissin, D.; Menichetti, M. Detection and Monitoring of Tunneling Induced Ground Movements Using Sentinel-1 SAR Interferometry. Remote Sens. **2019**, 11, 639. *https://doi.org/10.3390/rs11060639*
[55] Copernicus. "Observer: Copernicus - eyes on the EU's external borders", June 2019. *https://www.copernicus.eu/en/observer-copernicus-eyes-on-EU-external-borders*
[56] Frontex. "Boat carrying 13 tonnes of drugs intercepted as part of Operation Triton" by Frontex, December 2015. *https://www.frontex.europa.eu/media-centre/news/news-release/boat-carrying-13-tonnes-of-drugs-intercepted-as-part-of-operation-triton-QBbcCa*
[57] MaritimeFairTrade. "Using Satellite Images To Fight Cross-Border Maritime Crimes" by Lee Kok Leong, September 2019. *https://maritimefairtrade.org/using-satellite-images-to-fight-cross-border-maritime-crimes*
[58] *https://callisto-h2020.eu/*

[59] Via Satellite. “How Satellites Secure the Border” by Better Satellite World – SSPI. *https://interactive.satellitetoday.com/how-satellites-secure-the-border/*

[60] CATO Institute. “Drones on the Border: Efficacy and Privacy Implications” by David J.Bier and Matthew Feeney, May 2018. *https://www.cato.org/immigration-research-policy-brief/drones-border-efficacy-privacy-implications*

[61] Defense Daily. “CBP Wants Six VaDER Radar For Border Security Operations” by Calvin Biesecker, October 2013. *https://www.defensedaily.com/cbpwants-six-vaderradar-for-border-security-operations/homeland-security/*

[62] Statewatch. “Seeing through trees: Frontex commissions study on solutions for under-foliage detection” by Statewatch, February 2014. *https://www.statewatch.org/news/2014/february/seeing-through-trees-frontex-commissions-study-on-solutions-for-under-foliage-detection/*

[63] EUSI. “Border Control in Melilla: A Very High Resolution Look” by European Space Imaging, January 2019. *https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/*

[64] Department of Homeland Security. “Snapshot: Using Satellites and Data Analytics to Protect the Homeland” by DHS, September 2017. *https://www.dhs.gov/archive/science-and-technology/news/2017/09/29/snapshot-using-satellites-and-data-analytics-protect-homeland*

[65] Department of Homeland Security. “Snapshot: Using Satellites and Data Analytics to Protect the Homeland” by DHS, September 2017. *https://www.dhs.gov/archive/science-and-technology/news/2017/09/29/snapshot-using-satellites-and-data-analytics-protect-homeland*

[66] CATO Institute. “Drones on the Border: Efficacy and Privacy Implications” by David J.Bier and Matthew Feeney, May 2018. *https://www.cato.org/immigration-research-policy-brief/drones-border-efficacy-privacy-implications*

[67] Migration data portal. “Irregular migration” by MDP, September 2022. *https://www.migrationdataportal.org/themes/irregular-migration*

[68] European Space Agency. “On the move” by ESA. *https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Space_for_Sustainable_Development/On_the_move*

[69] UNOSAT. “Syrian Refugee Camps” by UNOSAT, March 2012. *https://unosat.org/products/633*

[70] Via Satellite. “People Watching: Tracking and Monitoring Migration” by Joanne Wheeler, July 24th, 2023, Via Satellite Magazine.*https://interactive.satellitetoday.com/via/articles/people-watching-tracking-and-monitoring-migration*

[71] Migrant at sea. “Satellite Imagery Used by Frontex to Detect and Rescue Migrant Boats” by Niels Frenzen, October 2015. *https://migrantsatsea.org/2015/10/12/satellite-imagery-used-by-frontex-to-detect-and-rescue-migrant-boats/*

[72] Via Satellite. “People Watching: Tracking and Monitoring Migration” by Joanne Wheeler, July 24th, 2023, Via Satellite Magazine. *https://interactive.satellitetoday.com/via/articles/people-watching-tracking-and-monitoring-migration*

[73] EUSI. “Border Control in Melilla: A Very High Resolution Look” by European Space Imaging, January 2019. *https://www.euspaceimaging.com/blog/2019/01/14/border-control-in-melilla-a-very-high-resolution-look/*

[74] Tingzon, I., Dejito, N., Flores, R. A., De Guzman, R., Carvajal, L., Erazo, K. Z., ... & Ghani, R. (2020). Mapping New Informal Settlements using Machine Learning and Time Series Satellite Images: An Application in the Venezuelan Migration Crisis.

[75] European Commission. “Weak Signals in Border Management and Surveillance Technologies” by Olivier Eulaerts and Geraldine Joanny, June 2022 *https://publications.jrc.ec.europa.eu/repository/handle/JRC128871*

[76] Quick Signal. “Mitigating Risk with Advanced Surveillance Technologies” by Quickset, May 2024. *https://www.quickset.com/mitigating-risk-with-advanced-surveillance-technologies/*

[77] Schreiber, D.; Opitz, A. A Novel Background Modelling Algorithm for Hyperspectral Ground-Based Surveillance and Through-Foliage Detection. 2022

[78] EDA. “European satellite constellation for vey low earth orbit to launch in two years” by EDA, March 2024. *https://eda.europa.eu/news-and-events/news/2024/03/06/european-satellite-constellation-for-very-low-earth-orbit-to-launch-in-two-years*

[79] GIM International. “EUSI and Albedo to deliver 10 cm resolution satellite imagery to Europe” by GIM International, April 2025. *https://www.gim-international.com/content/news/eusi-and-albedo-to-deliver-10cm-resolution-satellite-imagery-to-europe*

[80] EO4Society. “Quantum Computing for Earth Observation (QC4EO) Study - Executive Summary” by Gabriele Cavallaro, Amer Delilbasic, Edoardo Pasetto, Mattia Verducci, Tommaso Catuogno, Benjamin Marchand, Ilaria Siloi, Marco Tesoro, Jiri Guth Jarkovsky, December 2023. *https://eo4society.esa.int/wp-content/uploads/2024/01/QC4EO-study-Executive-Summary.pdf*

[81] *https://borderuas.eu/*

[82] European Commission. “What happens if my company processes data in different EU Member States?” by EC. *https://commission.europa.eu/law/law-topic/data-protection/rules-business-and-organisations/enforcement-and-sanctions/enforcement/what-happens-if-my-company-processes-data-different-eu-member-states_en*

[83] ESA. “Updated ESA Earth Observation Data Policy” by ESA, September 2023. *https://earth.esa.int/eogateway/documents/d/earth-online/esa-eo-data-policy*

[84] National Space Council. “Space Data Ethics: The Next Frontier in Responsible Leadership” by Users’ Advisory Group, December 2023. *https://www.nasa.gov/wp-content/uploads/2024/02/white-paper-space-data-ethics-2023-12-01-final-002.pdf*

[85] Programme of the European Union. “Ecosystem Code of Conduct”. *https://dataspace.copernicus.eu/ecosystem-code-conduct*

[86] European Economic and Social Committee. “Regulation on European data governance” by Giuseppe Guerini, Marinel Dănuț Muresan, April 2021. *https://www.eesc.europa.eu/pl/our-work/opinions-information-reports/opinions/regulation-european-data-governance*

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