Executive Summary

Enhanced Surroundings Awareness and Navigation for Autonomous Vessels

ESANAV

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Acronyms and Abbreviations

Acronym	Meaning
AIS	Automatic Identification System
ASV	Autonomous Surface Vessel
EO	Earth Observation
GNSS	Global Navigation Satellite System
HAPS	High-Altitude Pseudo-Satellite
MASS	Maritime Autonomous Surface Ship
OB(I)P	On-Board (Image) Processing
OTH	Over-the-Horizon
S&R	Search and Rescue
SatCom	Satellite Communications
TRL	Technology Readiness Level
VDES	VHF Data Exchange Format
VTS	Vessel Traffic Services

Acronym	Meaning
API	Application Programming Interface
COG	Course Over Ground
ESANAV	Enhanced Surrounding Awareness and Navigation for Autonomous Vessels
H2H	Harbour-to-Harbour
LEO	Low Earth Orbit
NRT	Near Real-Time
OOI	Object Of Interest
SA	Situational Awareness
SAR	Synthetic Aperture Radar
SOG	Speed Over Ground
UAV	Unmanned Aerial Vehicle
VHF	Very High Frequency (radio)

1. PROJECT CONTEXT

Autonomous Surface Vessels (ASVs) are rapidly approaching market-readiness, with numerous partly-autonomous and teleoperated systems either under development or already performing operational demonstrations for applications such as bathymetric surveying (SEA-KIT Maxlimer, Deep BV), maintenance of offshore installations (Thales Halcyon), and commercial shipping (Yara Birkeland, Maersk VISTULA-Class). By reducing or removing the need for onboard crew, such ASVs offer significant advantages in terms of the automation of monotonous tasks, improved safety for operating personnel in dangerous environments, and commercial cost savings via improvements to vessel operating efficiency and the centralisation of fleet operations into a small number of shore control centres.

In order the realise the full potential of these technologies, ASVs must be capable of operating effectively and safely in either remotely controlled or fully-autonomous modes across the full cross-section of maritime environments, from crowded harbours to open sea. The completeness and accuracy of ASV Situational Awareness (SA) is currently limited by the range, resolution and close-to-sea-level perspective of shipboard sensors, in addition to the extreme diversity of potential maritime hazards (both other vessels and various non-vessel collision hazards), obscuring adverse weather conditions, in addition to incomplete or inaccurate Automatic Identification System (AIS) information. These factors, combined with both the technical and psychological barriers to remote human supervisors maintaining an adequate level of environmental awareness, and the current immaturity of ASV maritime legislation, currently limit the range of maritime environments in which ASVs are able to operate safely and effectively with a high degree of autonomy.

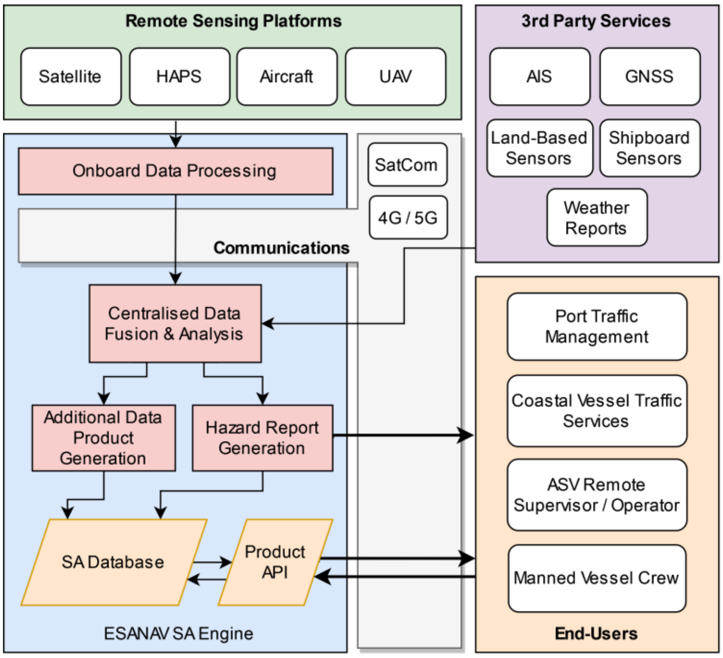
Furthermore, increasing rates of armed conflict, territorial disputes, sanctions, piracy and even sabotage poses in areas such as the Middle East, the Gulf of Guinea and South-East Asia constitutes a significant threat to shipping security, trade and supply chains around the globe. Additionally, cyber-attacks are a rapidly escalating concern in areas such as the Black Sea, Northern Scandinavia, the Arabian Peninsula and East Asia, but has also occurred on global scales; GNSS spoofing activities have been observed in the process of artificially shifting GNSS-derived vessel positions thousands of miles between US waters and Europe, Africa, and Indonesia, for purposes including masking illegal activity and leading unsuspecting vessels away from their intended course. All of these factors raise further concerns for the safety and security of uncrewed vessel operations, which must be addressed in parallel with the technological trend towards increasing maritime autonomy.

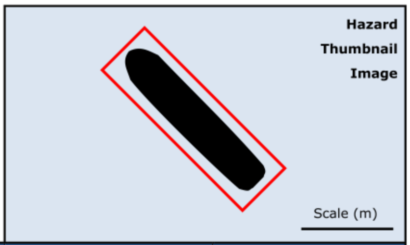
Developing maritime Situational Awareness (SA) capabilities to a level that facilitates safe vessel navigation and collision-avoidance in a variety of high-risk maritime environments is therefore a major enabler of commercially-viable Harbour to Harbour (H2H) autonomous operations, and the ultimate focus of the ESANAV study.

2. PROJECT OBJECTIVES

ESANAV constitutes a Phase-0/Phase-A feasibility study, in which multiple end-to-end remote sensing system concepts were developed based on a range of aerial and satellite platforms, Earth Observation (EO) payloads, advanced Computer Vision (CV) data processing techniques and multi-sensor data fusion architectures (Figure 2-1). The technical promise of these system concepts for delivering real-time, low-latency and high added-value maritime hazard perception, identification and tracking products were analysed, and their commercial propositions assessed both for navigation and collision avoidance applications, and a range of related maritime monitoring applications.

Of particular interest to the study is the High-Altitude Pseudo-Satellite (HAPS), an emerging class of stratospheric aerial platform designed to provide persistent sub-metre resolution imaging and over-the-horizon communication functions, with flight endurances of multiple months and flexible deployment capabilities compatible with dynamically evolving maritime Situational Awareness needs. When equipped with cloud-penetrating imaging payloads such as Synthetic Aperture Radar (SAR), these systems are expected to be capable of 24/7, real-time monitoring of maritime environments, including under adverse weather conditions where the utility of existing ASV sensor suites is significantly degraded.





	Quantity	Value	Uncertainty
Remote Sensing	Unique Hazard ID	OOI 00001	ID Match Score (%)
	Detection Time	YYYY/MM/DD HH:MM:SS.MS	Detection Score (%)
	Hazard Class	Vessel/Debris/Iceberg/...	Classification Score (%)
	Latitude	Latitude (AIS format)	Latitude Uncertainty (°)
	Longitude	Longitude (AIS format)	Longitude Uncertainty (°)
	Length	Hazard length (m)	Length Uncertainty (m)
	Heading	Angle of longest axis (°)	Heading Uncertainty (°)
	Course Over Ground	Extrapolated COG (°)	COG Uncertainty (°)
	Speed Over Ground	Extrapolated SOG (knots)	SOG Uncertainty (knots)
AIS	AIS ID	Vessel transponder ID	AIS Match Score (%)
	Report Time	Timestamp of AIS report	N/A
	Status	Reported Vessel Status	N/A
	Position	Latitude/Longitude	N/A
	Length	Reported Length	N/A
	Width	Reported Width	N/A
	Heading	Reported Heading	N/A
	Course Over Ground	Reported COG	N/A
	Speed Over Ground	Reported SOG	N/A

Figure 2-1: Example high-level system architecture concept (left) and hazard report (right) for ESANAV situational awareness services

A cross-section of relevant maritime stakeholders, including autonomous vessel operators, smart port developers, Vessel Traffic Services providers and maritime regulatory bodies, were engaged in order to accurately assess the hazard risk profiles of various maritime environments, define the key end-user requirements for remote hazard monitoring services, and understand the impacts of existing and future legislation on the adoption of considered technologies.

The ultimate output of the study is a multi-disciplinary technology and commercial roadmap detailing the primary technology development steps and expected time to market for the different proposed systems. In addition to this, recommendations have been made for roles that key stakeholders across the maritime, UAV/HAPS and space sectors should play in the development and realisation of selected SA system concepts.

3. RESULTS

Eight distinct maritime scenarios, ranging from busy ports through to high-latitude icebound waters, have been analysed and their hazard risk profiles assessed. Ten system proposals based on satellite platforms, HAPS, low-altitude Unmanned Aerial Vehicles (UAVs) and commercial aircraft were identified and traded off based on their high-level technical merits, system costs and component Technology Readiness Levels (TRLs). From these, five promising candidates were selected for detailed study and refinement through a multi-disciplinary technical analysis of platform, payload, data processing and communication infrastructure capabilities, in addition to a detailed commercial market analysis of the derived products and services.

From the aforementioned analyses, **three system architectures were selected as most promising for near-term commercial exploitation,** which together address six strategic maritime environments relevant to harbour-to-harbour navigation activities:

1) <u>**Sub-minute monitoring of localised regions of critical risk**</u>: Small fleet of station-keeping fixed-wing HAPS delivering continuous 24/7/365 monitoring of **ports** and **major shipping**

chokepoints, for Vessel Traffic Services augmentation, short-range collision risk detection and mitigation.

2) **Hourly wide-area monitoring of remote regions**: Use of expanded (virtual) satellite constellations to assist in long-distance vessel navigation and route planning in **deep sea** and **high-latitude icebound waters**, by providing a sufficiently up-to-date Near-Real-Time (NRT) picture of long-range hazards and their temporal evolution.
3) **Hybrid solutions for extended variable-risk regions**: Combination of low-frequency NRT satellite constellation observations and AIS monitoring to anticipate spikes in localised hazard risk across extended regions such as **coastal waters and shipping fairways**, and dynamically respond to these with tasked fixed-wing HAPS fleet real-time sensing capabilities, providing over-the-horizon range extension to Vessel Traffic Services and related maritime service providers (Figure 3-1).

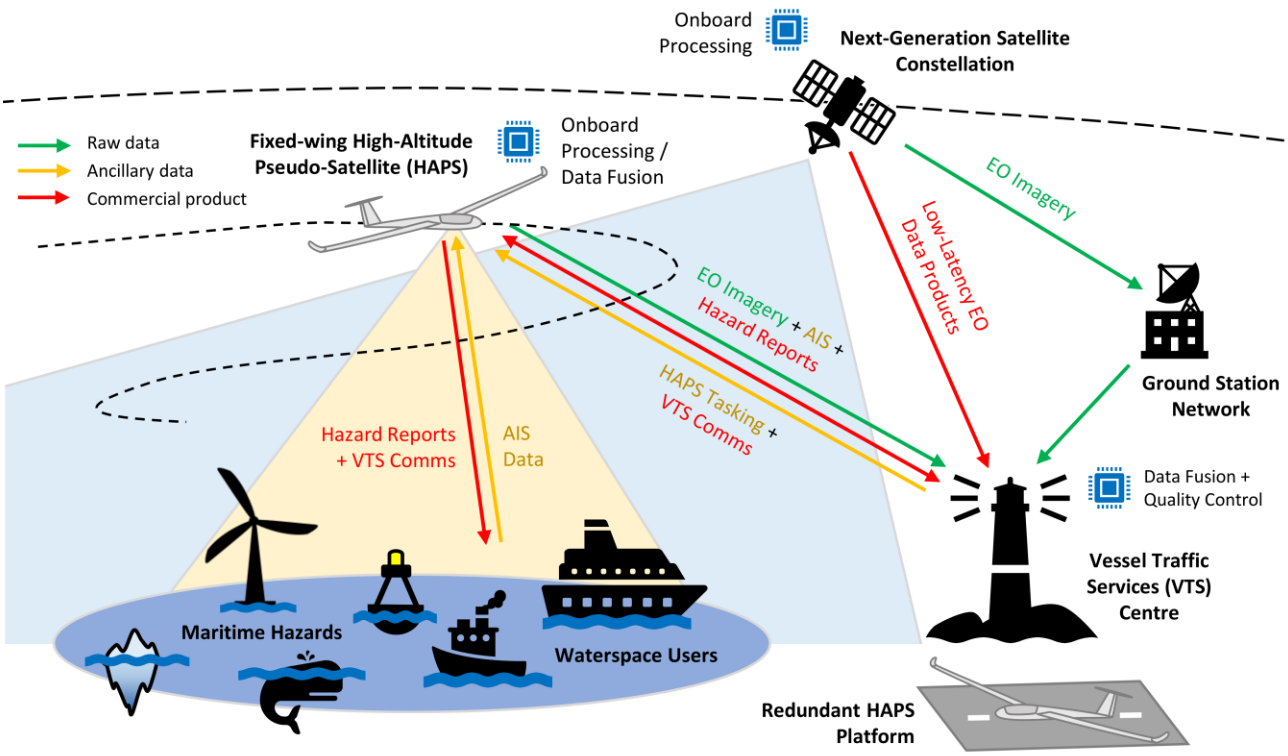


Figure 3-1: Illustration of a hybrid system concept combining deployable HAPS craft with satellite EO constellations for the over-the-horizon augmentation of maritime monitoring services.

In line with the ESA Open Space Innovation Platform (OSIP) Space for the Oceans initiative under which this study has been performed, this cross-section of maritime environments provides significant coverage of the highest-risk maritime environments relevant to enhancing the safety and efficiency of harbour-to-harbour navigation from ports through coastal and open water environments.

4. CONCLUSIONS

The primary conclusions regarding the three aerial and satellite platforms considered within the scope of the ESANAV study are as follows:

- **First-generation fixed-wing HAPS platforms** and their associated payloads are expected to be highly-compatible with the needs for metre-resolution, minute-level continuous monitoring of fixed ~100-400km^2 maritime regions of interest. However, **total systems costs on the order of €30-40M are a significant barrier** to end-to-end HAPS system ownership and operation outside high-budget maritime organisations or defence customers, motivating distributed "Platform as a Service" models for general maritime SA service provision. Furthermore, **year-round HAPS operations are currently limited to ±35° latitude** by solar power generation requirements; seasonal deployment at higher latitudes is possible during summer months, however this does not address the needs of high-risk arctic winter monitoring.

- In contrast, **low-altitude UAVs** face significant technical and commercial barriers to exploitation for SA applications, including environmental flight limitations, low TRL of autonomous launch, recovery and refuelling, and limited added-value over shipboard sensors when considering the total system costs of small-format quad-copter or larger helicopter-format UAVs. Such technologies are therefore **better-suited to other maritime monitoring applications,** such as rapid-response Search & Rescue (S&R) operations or smart port/offshore asset monitoring.
- The **revisit statistics of existing EO satellite constellations are unfavourable** for 24/7 regular-revisit applications, however with rapid ongoing maturation of optical and SAR satellite constellations, **virtual satellite constellation** solutions represent the most direct route to market, provided that high-priority tasking and low-latency downlink may be achieved with existing EO data architectures. Beyond this, **dedicated onboard processing (OBP)-capable satellite constellations** offer a technically feasible choice for achieving low-latency, robust, direct-to-user services, with **hourly revisit capabilities achievable with an optimised constellation comprising just 15-20 agile SmallSat-class platforms**. Such a constellation is well within current capabilities of national/international programmes or private aerospace consortia, and would enable a wide range of NRT applications.

In addition to **providing a complete, timely, all-weather picture of maritime hazards** (including those not broadcasting AIS information), a major benefit offered by EO situational awareness services is the opportunity to cross-validate AIS information broadcasts based on imagery-derived data products. Such functionality provides significant opportunities to **mitigate emerging threats such as GNSS spoofing, and identify AIS tampering activities**, relevant for behavioural monitoring capabilities beyond navigational safety in domains such as maritime security and regulatory compliance.

Low-latency maritime hazard perception, identification and tracking capabilities are a cornerstone of the ESANAV value proposition. **State-of-the-art AI algorithms** are rapidly approaching market readiness for maritime-sector applications, which along with improvements in their computational efficiency and **advances in the capabilities of Onboard Image Processing (OBIP) hardware** is enabling their in-situ deployment in both the UAV and space domains.

The high raw data generation rates of HAPS and satellite EO payloads mean that both classes of architecture benefit from OBIP capabilities; the **generation of reduced-volume of data products close-to-source** also enables the use of a range of low-bandwidth communication architectures (such as inter-satellite relays or direct-to-user delivery modes), decreasing global latency and providing redundancy for robust service delivery, with respect to traditional ground-based data processing chains.

5. OUTLOOK

The ultimate outcome of this project is a **multidisciplinary 20-year roadmap** (Figure 5-1) for the development and implementation of the selected EO mission concepts, summarising the expected timescales for technology development, regulatory maturation and commercial activities, along with major system achievement milestones for each maritime scenario.

Initial versions of each proposed system concept may be demonstrated as early as 2025-2027 (Figure 5-2), following which the stepwise maturation of advanced technologies, including high-resolution thermal-infrared satellite constellations and second-generation HAPS craft, is expected to realise the full potential of these systems for remote sensing products and services by the mid-to-late 2030s.

In order to achieve this however, the **participation of a range of public and private stakeholders** across the **maritime, HAPS/UAV and space sectors** is necessary in order to ensure that component technology roadmaps remain compatible with the needs of maritime end-users over the coming two decades.

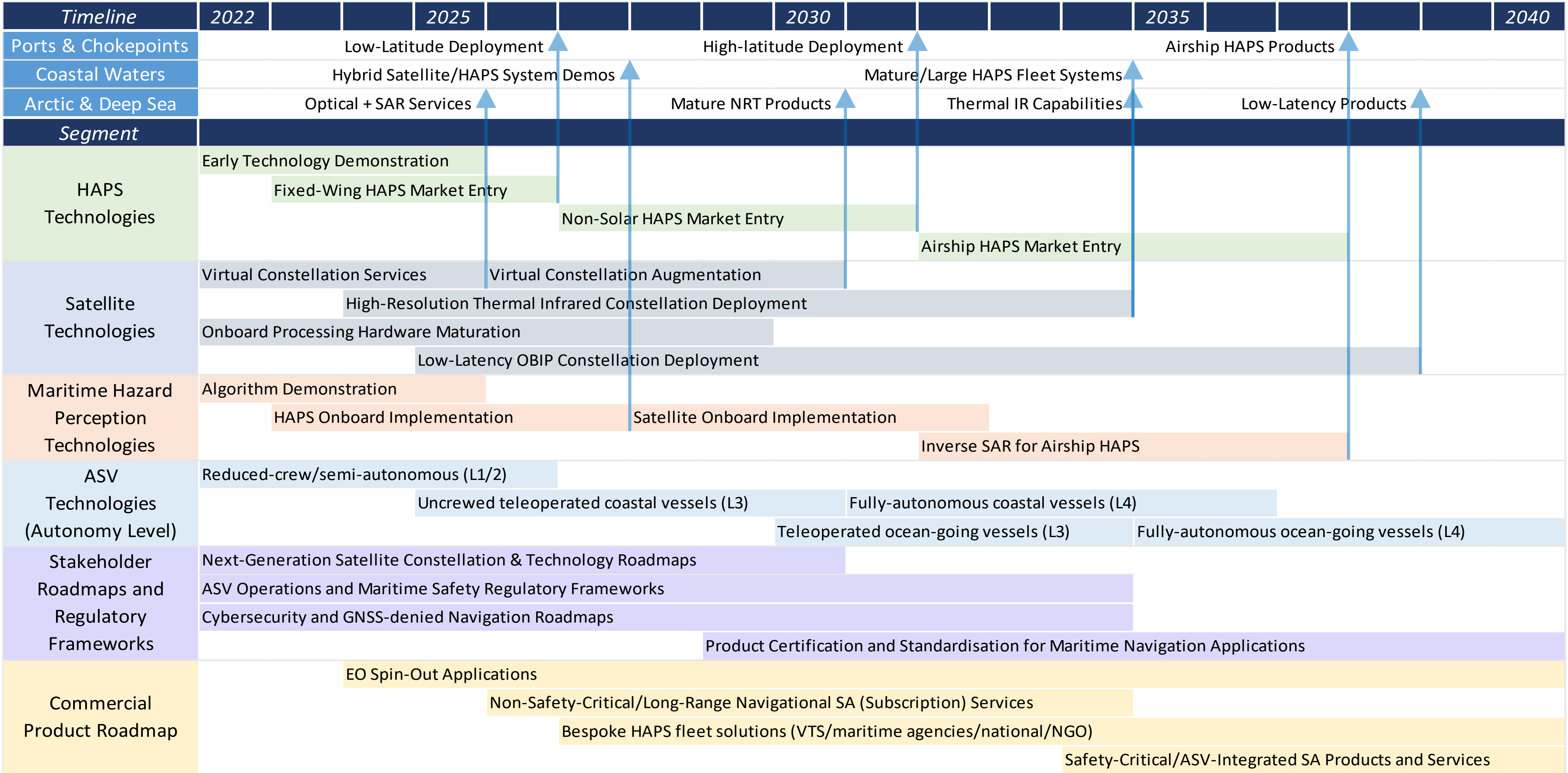


Figure 5-1: ESANAV multi-disciplinary roadmap of envisaged technology and commercial development activities and milestones

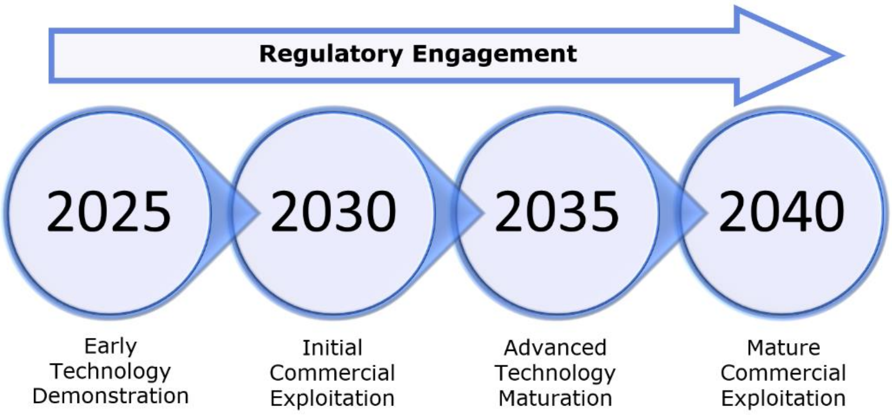


Figure 5-2: Commercial implementation roadmap for ESANAV technologies

Significant certification and liability challenges surrounding the **use of third-party situational awareness information for time- or safety-critical decision-making processes** mean that EO services must act as an aid to navigation and collision avoidance in the short-term, delivering added-value through applications such as long-range navigation optimisation or human-in-the-loop functions.

The ultimate goal of ESANAV - the **direct integration of remote sensing data products with autonomous decision-making processes for harbour-to-harbour navigation applications** - must therefore be developed through close engagement with maritime safety and standards agencies to define ASV operational frameworks, alongside the mature demonstration of robust, high added-value remote sensing SA service capabilities. If successful, future EO-derived SA services may be envisaged as an extension to AIS and the future VHF Data Exchange System (VDES) standards for maritime status reporting, adding benefits including vessel data cross-validation and non-AIS hazard monitoring functionality.

In the meantime, ESANAV-style SA services are expected to provide significant value to a range of other maritime applications including Vessel Traffic Services (VTS) providers, traditional fully-crewed vessels and maritime surveillance operations. The following major commercial benefits are identified:

1. **Non-safety-critical/long-range vessel navigation aids:** Enable fuel and insurance net cost savings to shipping fleet operators through global, hourly, Near-Real-Time (NRT) collision hazard and sea state monitoring by virtual satellite constellations. This is especially suited to high-latitude waters, for the de-risking of navigation of dynamic ice floes and the safe and sustainable exploitation of high-value emerging arctic shipping routes.
2. **Bespoke solutions for maritime service augmentation:** Deployment of hybrid HAPS and virtual satellite constellation architectures, to facilitate dynamic coastal/offshore monitoring and communications relay over regions up to 400km in diameter. This enables the extension of existing services, such as Vessel Traffic Services (VTS), Search and Rescue (S&R) operations, security and related maritime operations performed from centralised shore-based centres, to high-risk chokepoints and extended coastal/offshore regions that are not feasible to cover with shore-based sensor networks.
3. **Spin-out EO applications:** Development of commercial low-latency imagery products and services using hourly satellite or minute-interval HAPS imagery for a range of applications, including responsive security and law enforcement, environmental and pollution monitoring, as well as smart port arrival time estimation and shore-based asset monitoring. Similar applications outside maritime domains related to human activities and natural process monitoring on sub-daily timescales, including smart cities management and disaster response coordination, will also be facilitated through the realisation of regular-revisit 24/7 monitoring capabilities.