Satellite Monitoring of Underwater Cultural Heritage

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Acronyms and Abbreviations

AIS	Automatic Identification System
AOI	Area of Interest
EEZ	Exclusive Economic Zone
EO	Electro-optical
ESA	European Space Agency
IHS	Information Handling Services
IMO	International Maritime Organization
IRCS	International Radio Call Sign
IUU	Illegal, unreported, and unregulated activity
MAST	Maritime Archaeology Sea Trust
MMSI	Maritime mobile service identity
MPA	Marine Protected Area
NM	Nautical Mile
OM	OceanMind
SAR	Synthetic Aperture Radar
SRA	Strategic Risk Assessment
UTC	Coordinated Universal Time
VIIRS	Visible Infrared Imaging Radiometer Suite
VMS	Vessel Monitoring System
VOI	Vessel of Interest

Introduction

Heritage crime[1] has threatened underwater cultural heritage (UCH) ever since the first artefacts were retrieved from the seabed. The popularisation of recreational diving using SCUBA equipment after World War Two created a boom in underwater discoveries but also exposed many sites to disturbance for the first time. As early as the 1960s archaeologists realised that many underwater sites were being looted (Bass 1966: 17; Muckelroy 1978: 14). The protection of UCH remains a major problem. There are few legal frameworks in place to combat crime at sea. Many sites around the world are poorly or inadequately monitored, leaving them vulnerable to both heritage crime and accidental damage from commercial activities such as fishing. Even the most inaccessible deepwater sites and remote locations are at risk. UCH is a finite resource that is diminished with every site and artefact lost (Keith & Carrell 2009).

Methods to combat heritage crime vary from community engagement (Campbell *et al.* 2018) to physical intervention, like cages (Radić Rossi 2014). The protection of UCH presents a challenge to the coastguard, police, border security and customs. The 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage creates a framework for best practice, while the Secretariat has worked on initiatives to combat the looting and trafficking of UCH. However options are limited. While the creation of Marine Protected Areas (MPAs) or archaeological parks can offer a level of protection, they also place targets on areas that attract criminals (Weekers *et al.* 2021). Annual dive monitoring of UCH sites is an effective method of identifying where criminal activity has occurred, but it lacks the capacity to intervene in active looting.

The last two years, however, have heralded the potential for an entirely new, digital and cost-effective method for reducing heritage crime both at sea and on land. The availability of large-scale digital datasets, powerful computer processing, and the development of artificial intelligence methods are revolutionising the ability not just of governments but archaeologists and the public to monitor UCH. Satellite technologies that are now publicly accessible include electro-optical imagery (EO), synthetic aperture radar (SAR), and Automatic Identification Systems (AIS). Combined, these datasets provide insights into the behavioural patterns of legal and illegal events. The result can be the real-time monitoring of at-risk sites, or investigation of criminal activity that has occurred in the past through archived digital data. This White Paper outlines the datasets and methods currently available, and how interested heritage managers can implement these either as cultural property protection or as part of criminal investigations.

1 'Heritage crime' is an umbrella term for criminal activity that targets cultural heritage. Offences include looting, illegal excavation, burglary and theft, criminal damage, unauthorised development, smuggling, and anti-social behaviour (Bradley et al. 2012).

Development

The first satellite for Earth observation, Landsat 1, was launched in 1972 and carried a multispectral scanner. The technology has since grown exponentially, spawning spaced-based remote detection sub-disciplines in many scientific fields including archaeology, ecology, and oceanography. Today, there are a range of Earth observation missions collecting publicly available data, led by the European Space Agency's Copernicus Programme of twenty Sentinel satellites and NASA's sixteen Landsat satellites. Globally, 1,460 Earth observation satellites have been launched during the last twenty years, and that number is growing. The range of instruments available now include Synthetic Aperture Radar (SAR), Microwave Radiometer (MWR), Sea and Land Surface Temperature Radiometer (SLSTR), and Ocean and Land Colour Instrument (OLCI).

Satellite data has been widely deployed for identification and monitoring of heritage crime at terrestrial sites (Parcak *et al.* 2016; Parcak 2019). The use of historical imagery, such as Cold War spy satellite data, allows for comparison of archaeological sites in the 1960-70s and today (Casana *et al.* 2023). In maritime archaeology, satellites have been used for UCH prospection, including shipwrecks (Baeye *et al.* 2016) and paleolandscapes (Westley 2021). The large-scale Maritime Endangered Archaeology (MarEA) project identifies at-risk coastal heritage sites through satellite imagery (Andreou *et al.* 2020). Using the same techniques to identify heritage crime at sea has proved more difficult since the evidence is generally not visible from space. Since 2019 the Maritime Observatory[2] has pioneered new techniques to provide satellite data to heritage agencies, law enforcement, universities, charities and individuals investigating heritage crime at sea.

The costs and access to satellite data have dropped hugely over the last ten years. This White Paper serves as a guide to applying these methods to UCH. While there can still be considerable costs for certain types of data, not least the need for experienced analysts, remote monitoring is increasingly available to heritage managers.

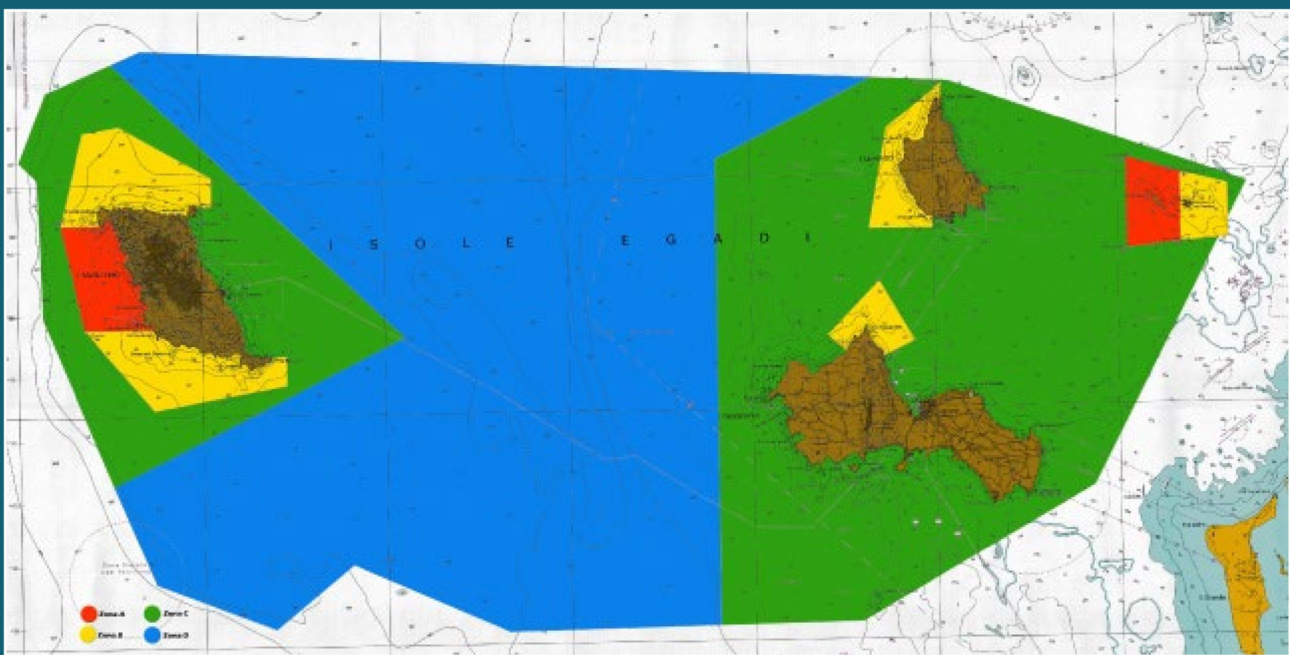
2 A partnership between MAST and OceanMind to detect and deter unauthorised salvage and monitor for PPWs using a combination of satellite technology, HUMINT and OSINT and AI (https://www.thisismast.org/maritime-observatory.html).

Figure 1

Above, in 1905 sponge divers recovered 30 ancient anchors from Cabo de Palos, Spain (Fita 1906: 157); right, in 1928 fishermen discovered a statue of Zeus or Poseidon off Cape Artemision, Greece (The Illustrated London News 1928a, 675).

Figure 2

Map of the Egadi MPA with the four zones of protection highlighted.
Red = No Take (Diving only allowed via Guided Tours in Summer),
Yellow = General Protection (Diving only allowed via Permit), Green = Partial Protection (No restriction on diving), Blue = Minor Limitations (Trawling Allowed) (UNEP/MAP-SPA/RAC).



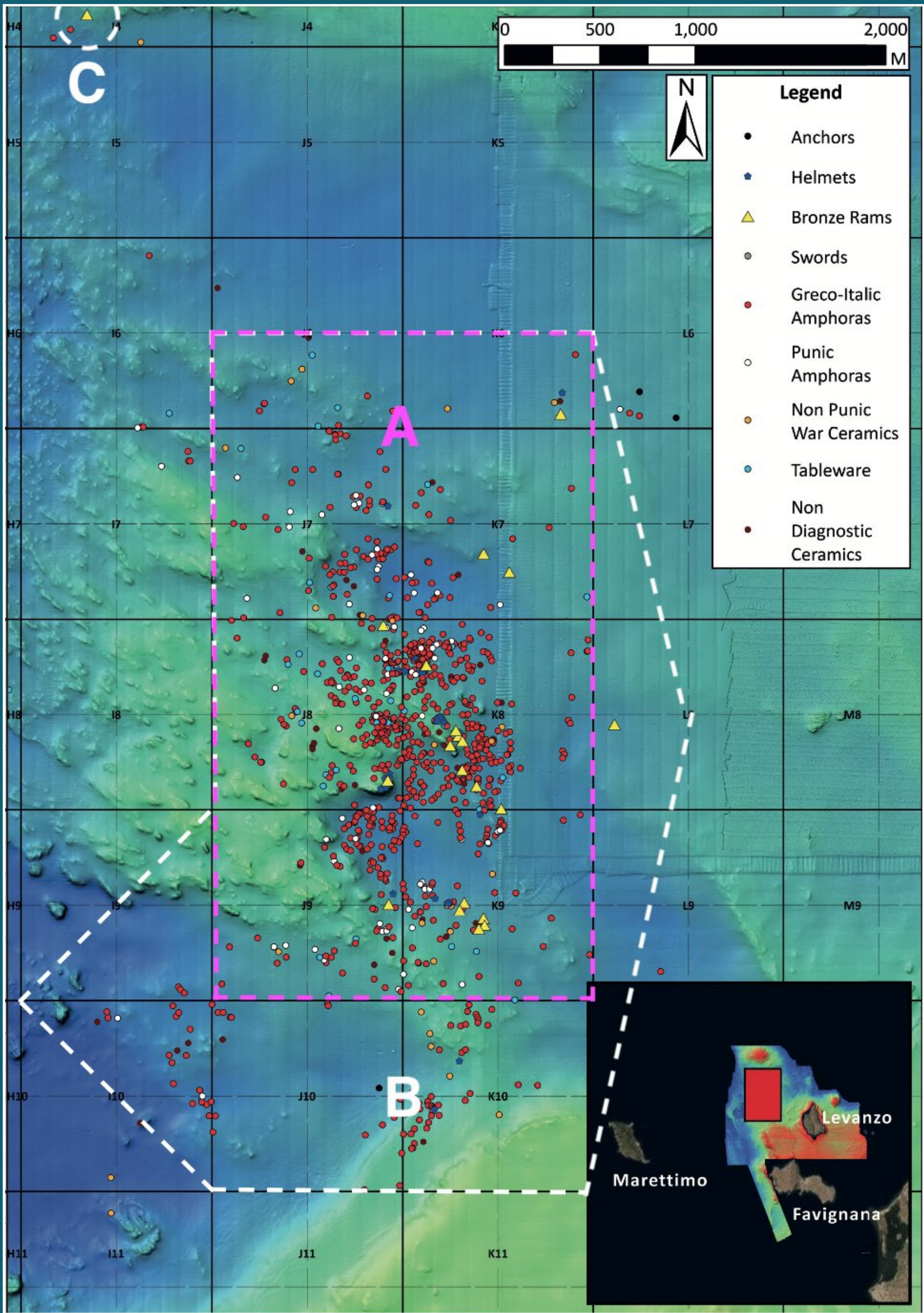


Figure 3

Site Plan of the Battle of the Egadi Islands. The study area covers Areas A & B with a 1 NM buffer zone surrounding it (Soprintendenza del Mare Regione Siciliana/RPM Nautical Foundation/Global Underwater Explorers/MAST).

The Egadi Islands MPA Case Study

This White Paper presents a monitoring methodology with examples from the Egadi Islands Marine Protected Area. It is Europe's largest MPA, encompassing 53,992 hectares off western Sicily (D'Anna *et al.* 2016) (Figure 2), and the area includes the remains of the only ancient naval battlefield discovered, the Battle of Egadi Islands[3] (241 BC) (Tusa *et al.* 2021). The discovery of the archaeological site in 2001 was prompted by a Carabinieri investigation into a looted bronze warship ram that was on display in the offices of a dentist in Trapani, the Sicilian city nearest to the Egadi Islands. The undeclared ram had been pulled up by fishermen within the MPA. Scattered across the battlefield are numerous rare artefacts, such as warship rams, helmets, amphorae, and coins, whose portability and high market value make the site a high risk from looting. Since the site lies 3NM offshore, only distantly visible from the islands of Marettimo, Favignana, and Levanzo, it is difficult to protect using traditional monitoring such as marine patrols.

In the Spring of 2023 the Maritime Observatory analysed data from the Egadi site from January 1 to December 31, 2022. The study area of interest (AOI) comprised 11 km^2 (3.2 NM^2) and a 1 NM buffer (Figure 3). This used archival AIS and remote sensing data acquired from commercial sources. The study was conducted as a retrospective timeframe, replicating a law enforcement investigation. It also demonstrates the potential of real-time monitoring, using the same methods. The study identified risks to the site from fishing activities and 'dark' vessels operating over the site.

3 Also known as the Battle of the Aegates.

Remote Sensing Data Sources

The Maritime Observatory methodology, first developed by OceanMind for monitoring illegal fishing (Gross 2018), draws on multiple datasets to create an interdisciplinary model of vessel behaviour. This section outlines the most widely available data sources. Not every data type is suitable to every context, but a general awareness of the benefits and limitations of the available methods will allow readers to assess what suits their own investigation or monitoring system. Overlapping data sources can be used to gather complementary information. For example, AIS transmission data can identify most vessels operating in a MPA while electro-optical imagery can reveal additional vessels which are either not equipped with AIS or potentially have turned their transmissions off to conceal illicit activity.

Choosing data sources is key. Each produces different types of data (and cost), depending on the size of the study area and reporting frequency (e.g. daily, weekly, monthly), as shown in Table 1. Approaches need to be adapted depending on the remoteness of the site, or factors such as cloud cover and wave height, which can hide activity. Some datasets can create millions of datapoints which would quickly overwhelm human analysts. Artificial Intelligence or Machine Learning can help to sort large-scale data, as discussed below.

Table 1. Comparison of some of the data sources available for remote monitoring

Data Source	Revisit Frequency	Cost	Overview
Automatic Identification system	Real-Time Coverage	$–$$	Maritime collision avoidance system transmitted on marine VHF radio. Some providers offer free real-time satellite derived AIS data and data received by terrestrial antennas via online platforms. Commercial archival datasets are widely available. The system is not tamper-proof. Vessels can transmit poor, false, or incomplete data and the transmitter can be turned off by the operators.
Electro-optical	Variable, 1–6 days	0–$$$	Optical data can provide information about a vessel's activity, as well as the vessel's position. Several providers offer global coverage with imagery updated every 5 days for free. Commercial providers may update imagery more regularly, offer bespoke tasking, and higher resolution imagery. EO imagery can only operate in daylight and is heavily influenced by weather conditions, particularly cloud cover.

Data Source	Revisit Frequency	Cost	Overview
Synthetic Aperture Radar	Variable, 1–6 days	0–$$$	Captures an image of an area based on the return characteristics of the particle beam reflected by the surface of the earth. Several providers offer global coverage with imagery updated every 5-6 days for free. Commercial providers may update imagery more regularly, offer bespoke tasking, and higher resolution imagery. SAR imagery is often lower resolution than EO but can operate equally well by day or night. Less influenced by weather but sea state may affect results.
Visible Infrared Imaging Radiometer Suite	14 hours (but data acquisition may not coincide with local nighttime)	$$$	Scanning radiometer. The VIIRS day/night band (DNB) collects low-light imaging data in the visible spectrum to enable the detection of light sources present at the Earth's surface. This includes ships operating at night and using artificial light to conduct operations. Currently only available commercially.

Automatic Identification System (AIS)

AIS is a maritime collision avoidance system transmitted on marine VHF radio. It provides a variety of information including position, speed, course and identity data, as inputted by the transmitting vessel. It was designed for safety to help vessels at sea track other nearby vessels. The system is regulated by the International Maritime Organization (IMO) International Convention for the Safety of Life at Sea (SOLAS).

AIS transmissions are line of sight, meaning Earth's curvature limits its horizontal reception. However, its vertical transmission is readily captured by commercial satellite arrays. Experiments detecting AIS transmissions using satellite-based receivers began around 2005: commercial data collection began in 2008. Now, more than 100 satellites carry an AIS receiver as part of their payload. This study used a combination of AIS data collected by commercial satellite and terrestrial antennas to monitor vessel activity within the Egadi MPA between 01 Jan – 31 Dec 2022. The data was assessed for possible risks from all maritime activities that could have impacted the site (Figure 22).

In busy waterways AIS monitoring may need support from machine learning systems to identify specific vessels or activity amidst the volume of background traffic. For instance, an average of 1,300 commercial vessels were detected crossing the Strait of Dover per week in 2023 (ONS 2024), generating millions of data points. Checking each of these AIS tracks as well as the additional non-commercial traffic could quickly overwhelm a human operator.

Figure 4

AIS track of a research vessel operating inside the Egadi MPA (Maritime Observatory).

Figure 5

Comparison between free and commercial EO product resolutions. Note these images were taken just 25 minutes apart at the same location. The S-2A imagery at 10m resolution (L) is sufficient to enable identification of a dredger working close to an MPA. The higher resolution GeoEye-1 imagery at 50cm resolution (R) allows the individual vessel to be identified (see inset) and deck activity assessed with a higher degree of confidence (Maritime Observatory).

AIS can provide critical data for identifying illegal actors when their AIS is transmitting. But it is not tamper-proof. It can transmit poor, false, or incomplete identity data and the transmitter can be turned off by the operators. Vessels that do not wish to be detected routinely turn off their AIS transponder or interfere with the transmissions (Richardson, 2023). The most sophisticated criminal activity at sea may hide behind false AIS transmissions that place a vessel far from its actual location. However, inconsistencies in AIS data or turning off transmissions can also flag potential illicit activity, although care is needed in identifying suspicious interference. There can also be innocent reasons for signal interruption, including weak signal strength, satellite coverage and receiver capacity. Not every vessel is required to operate with AIS; regulations vary by region and industry with smaller vessels often exempt. Many potential vessels of interest, including diving vessels and RIBs are too small to require AIS, and thus cannot be tracked using this technology. Military and law enforcement vessels may also not transmit AIS data while on operations. Collectively vessels that do not transmit AIS data are known as 'dark vessels'.

Vessel Monitoring Systems (VMS)

In addition to AIS, Vessel Monitoring System (VMS) and Inshore Vessel Monitoring (I-VMS) are mandatory in some countries. In the UK the former is compulsory for fishing vessels over 12m and the latter for fishing vessels under 12m. While these systems do not exclude 'dark' vessels, (vessels with AIS, VMS, or I-VMS turned off), they provide important information when in operation, or when they are turned off prior to entering a restricted or protected area. VMS data was not available for the Egadi MPA and so was not used in this study.

Electro-optical (EO)

Electro-optical systems are increasingly being used to monitor vessel traffic and detect 'dark' vessels. The imagery also provides an alternate insight to other remote sensing data sources because it offers some information about a vessel's activity, such as indicating a wake if travelling at speed, as well as the vessel's position.

Popular open-source products include the Sentinel-2 mission, a European Space Agency (ESA) constellation[4] of two polar orbiting satellites (Sentinel-2A and Sentinel-2B) that carry multispectral imagers. Sentinel-2 offers images with 10m pixel size, suitable for vessel detection. The revisit[5] frequency of each single satellite is ten days, and the combined constellation revisit rate is every five days, becoming more frequent nearer the poles.

4 A group of satellites working together to achieve a common purpose.

5 The time between the satellite observing the same point on earth.

There are also a wide range of higher resolution commercial products that allow more detailed analysis of a vessel's activity (Figure 5). High resolution EO imagery is an effective tool for identifying maritime targets as small as a jet ski and determining the vessel's activity, such as anchoring, fishing or simply transiting. EO systems are limited, however, to daylight hours and are heavily influenced by weather conditions. Cloud cover often makes optical images unusable. Few target vessels operating in coastal waters will remain over a site long enough to be detected by EO imagery unless commercial services are specifically tasked for the purpose, which may also not be cost effective. EO imagery is best used in conjunction with SAR systems to reduce the potential gap between image collection.

Electro-optical satellite imagery was collected during the Egadi MPA study to monitor any possible 'dark' vessel activity. This required correlating all detections within the EO imagery with the corresponding AIS tracks (Table 2). Vessel detections that could not be correlated with an AIS track were flagged as probable 'dark vessels'. Data was acquired during local day time through the Sentinel-2 constellation for the two most active months.

Although this remote sensing technique can significantly enhance site monitoring, it should not be used in isolation. It was possible to maintain reasonable EO coverage of the Egadi MPA during the monitoring period. However nuances such as the type of fishing activities allowed in different zones could not be adequately monitored with this type of remote sensing alone. More traditional measures, such as patrol monitoring and logbook information would still be required to verify compliance.

Table 2. Example Sentinel-2 detection of a research vessel, which was correlated with AIS.

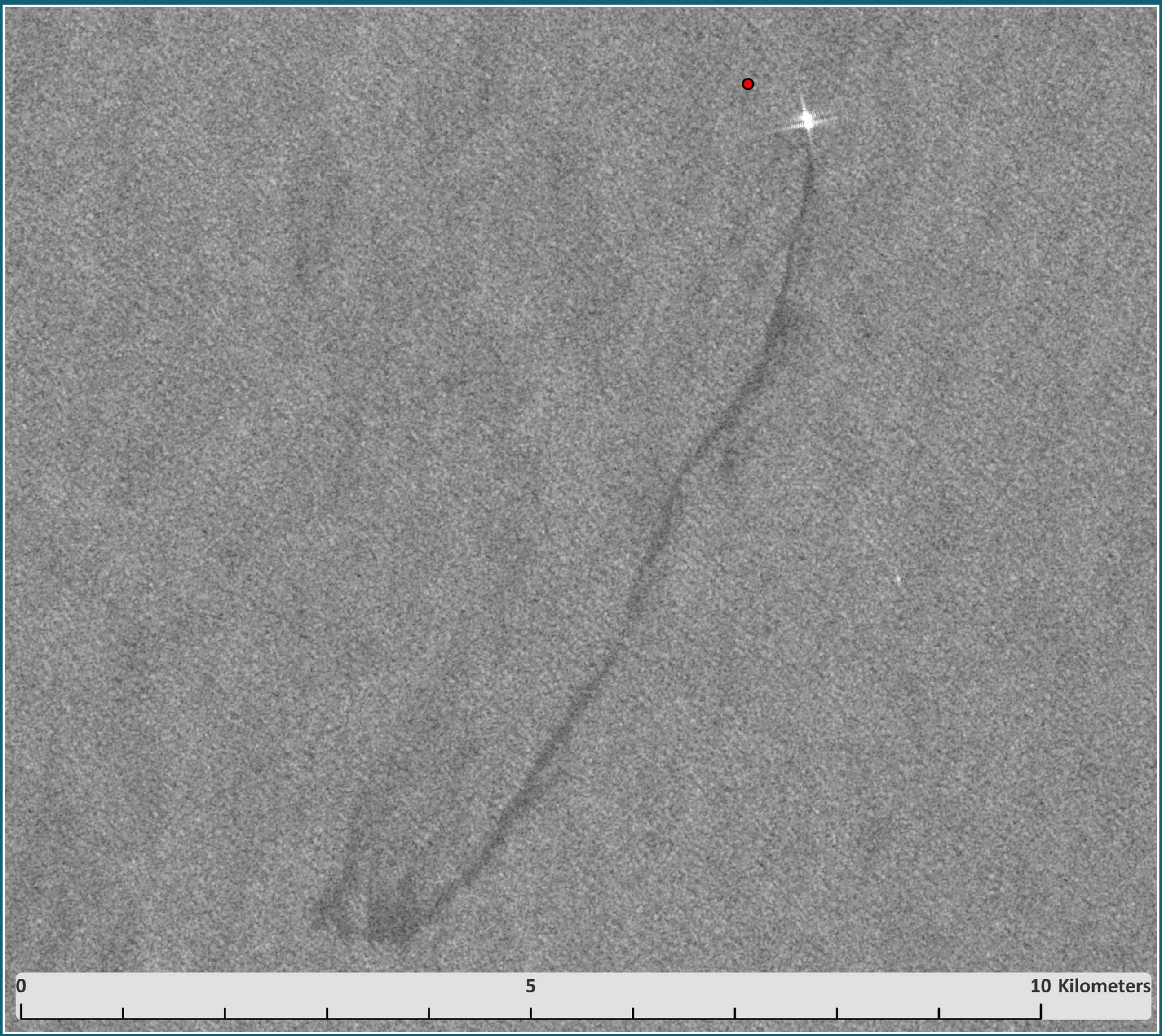
Date & Time	Latitude	Longitude	Risk	Size	Description	Thumbnail
28Aug2022 12:06Z	12.2847	38.0162	NA	35–45m	Research vessel slowly transiting in the buffer of the AOI.	

Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar images capture an image of an area based on the return characteristics of the particle beam reflected by the surface of the Earth and objects within it at that precise moment. This can be used to detect vessels of different sizes and classes as well as some types of activity. Most commonly SAR data is used to confirm the presence of a vessel within a protected area. Recent archaeological related studies using SAR data have also included initiatives to detect oil escaping from historic wrecks as they decay, and catastrophic oil releases triggered by unauthorised salvage work (Figure 6).

Figure 6

S-1 SAR detection of an oil spill released by an IUU salvage vessel targeting a historic wreck in the Java Sea (Image: MAST).



Popular open-source SAR products include the Sentinel-1 mission, an ESA constellation of two polar orbiting satellites (Sentinel-1A and Sentinel-1B) launched in April 2014 and March 2016 respectively. The Sentinel-1 satellites have a global coverage with a visit frequency of every six days. SAR imagery was not analysed during the Egadi MPA but other Maritime Observatory monitoring programmes use the Sentinel-1 mode Interferometric Wide Swath (IW) which has a 20m pixel size.

Maritime Observatory detections of vessels are based on the detection profile and environmental parameters at the time the image was taken and are classified by size:

1. **Merchant vessel detections**
   The profile of the detection strongly suggests the presence of a large vessel >130m. These detections could match merchant cargo vessels.

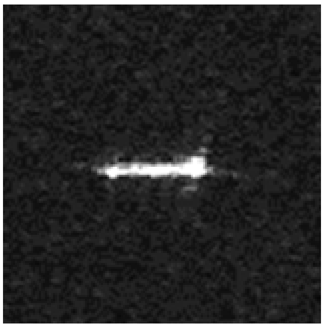
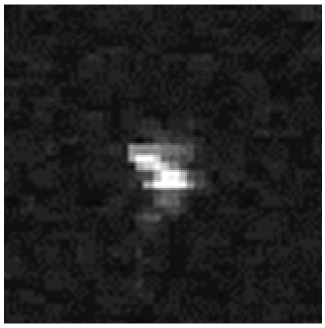
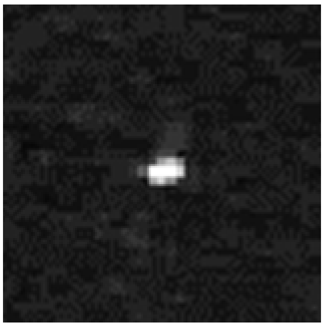
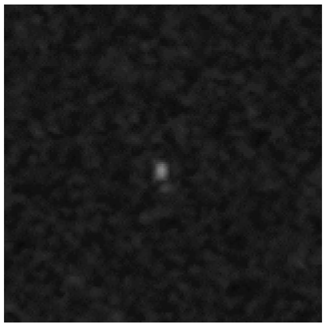
2. **Large scale vessel detections**
   The profile of the detection strongly suggests the presence of a large vessel 75–130m. These detections could match small cargo vessels, large salvage vessels or large fishing vessels.

3. **Medium scale vessel detections**
   The profile of the detection strongly suggests the presence of a medium vessel 30–75m. These detections could match medium sized salvage or diving vessels or medium sized fishing vessels.

4. **Small scale vessel detections**
   The profile of the detection suggests that there may be a medium to small vessel <20–30m. These detections would match most small salvage and diving vessels or a pleasure craft. However, due to the weak detection profile it could be a false detection.

As Table 3 illustrates, the sizes and shapes of small to medium size detections are not always well defined in lower resolution imagery and vessel types cannot be determined accurately. This limitation restricts the use of SAR for identifying specific vessel types in high traffic coastal areas, where many vessels may have the same size profile, such as yachts, pleasure vessels, and small fishing vessels. Resolutions can be increased with commercial products but are costlier. Commercial SAR with a resolution between 3-6 m is very effective at detecting ‘dark vessels’ and can provide better indication of vessel type for larger detections.

Table 3. SAR imagery vessel profile breakdown at 20m resolution

Merchant vessel detection	Large vessel detection
	
SAR detection that matches the profile of a merchant vessel	SAR detection that matches the profile of a large vessel
Medium vessel detection	**Small vessel detection**
	
SAR detection that matches the profile of medium vessel	SAR detection that matches the profile of small vessel

Few diving vessels operating in coastal waters will remain over a site long enough to be detected by SAR imagery unless commercial services are specifically tasked for the purpose. SAR imagery is best used in conjunction with EO systems to reduce the potential gap between image collection, and as SAR detections can be captured equally well by day or night. Although SAR data is less influenced by weather conditions, poor weather can reduce the ability to detect small vessels in a rough ocean.

Visible Infrared Imaging Radiometer Suite (VIIRS)

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a sensor that collects imagery and radiometric measurements in visible and infrared bands of the electromagnetic spectrum. The VIIRS day/night band (DNB) collects low-light imaging data to enable the detection of light sources present at the Earth's surface. This includes light emissions that may be from ships. Vessels carrying out fishing or sub-surface operations at night typically use deck lights which stand out against the dimmer light emitted by transiting vessels. VIIRS therefore represents a useful means to detect vessels of any size operating at night.

Benefits of the technology include global coverage with a revisit period of just 14 hours. The sensor is affected by environmental factors and depends solely on the strength of light emissions from a vessel. Limitations of the technology therefore include the possibility that some target vessels will not create sufficient light for the sensor to detect. The data is available as an algorithm-processed dataset with multiple parameters and a score linked to every detection that indicates the likelihood of a detection being a possible vessel (high or low confidence) (Figure 9). Due to the range of environmental variables, the confidence of these detections being real targets is lower than other data sources. Therefore, where possible it is important to verify VIIRS data against other sources such as SAR to confirm detections.

The Egadi MPA study used data collected during local night-time throughout 2022 through the Suomi National Polar-orbiting Partnership (Suomi NPP) NOAA-20 and NOAA-21 weather satellites. This service is commercially available.

Open-Source Intelligence (OSINT)

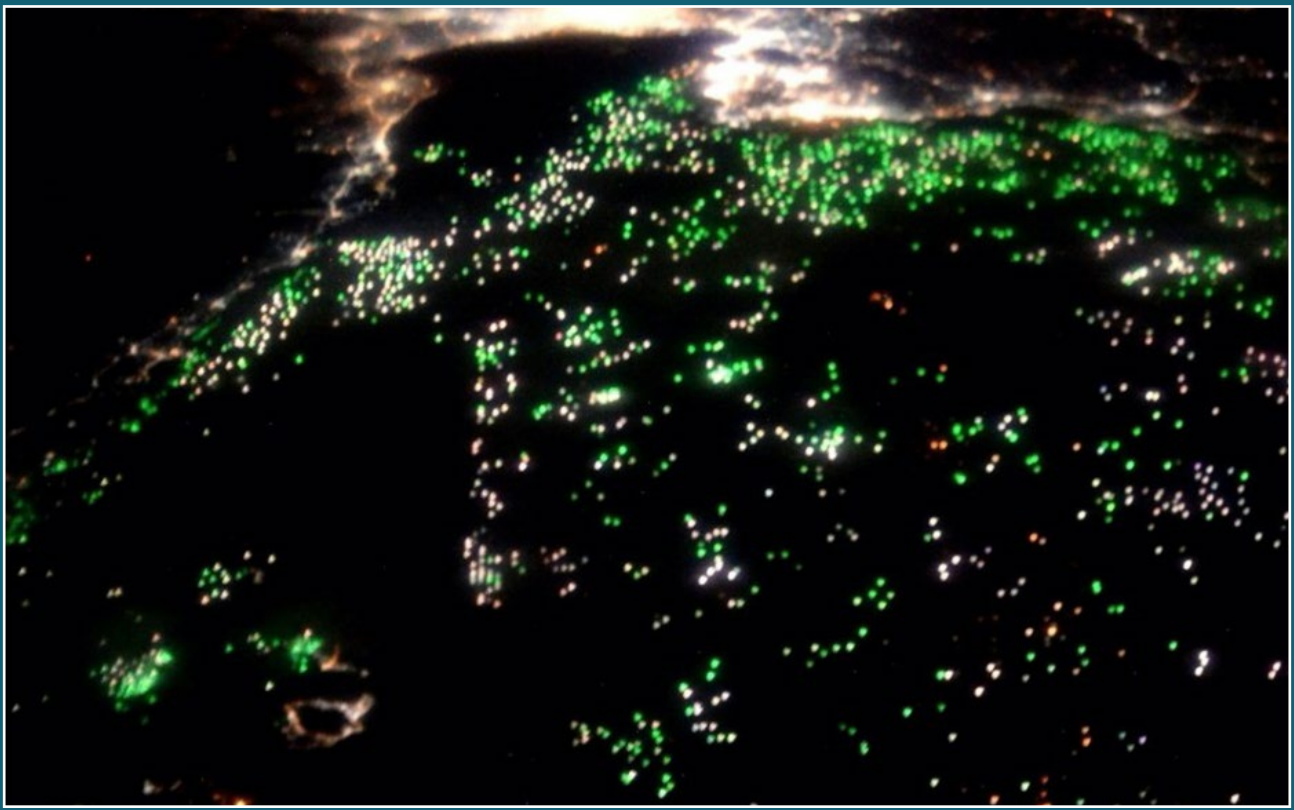
Open-Source intelligence (OSINT) is the gathering and interpreting of publicly available information on social media, websites, and published documents. Made popular by media outlets such as the New York Times, Bellingcat, and Forensic Architecture during conflicts in Iraq, Syria, and Ukraine, OSINT scrapes available data to gather intelligence on a specific subject or site. The data types and quality, as well as the methodologies used to assess them, vary widely. In the case of maritime heritage crime investigations, data might include social media posts by persons of interest on vessel position or activity, vessel routes or cargo manifests, or information on company websites. Metadata from social media posts, for example, can help to identify data relating to location and timestamps.

Machine Learning

Artificial intelligence, machine learning, and deep learning are three different methodologies for analysing data. OceanMind uses machine learning to support analysts by noticing trends in vessel behaviour. Datasets from vessel identification and monitoring systems can be very large, often exceeding 1 million data points in a single area. It would require significant resources for human analysts to effectively monitor all these vessels. Instead OceanMind's proprietary algorithm was trained on millions of datapoints. It can analyse vessel type, fishing activity, and possible risks in real-time and provide alerts. These do not replace humans but help analysts focus on suspicious or non-compliant vessels, thus building crime behavioural models.

Figure 7

Photograph showing light emissions from fishing boats operating at night in the Gulf of Thailand (OceanMind).



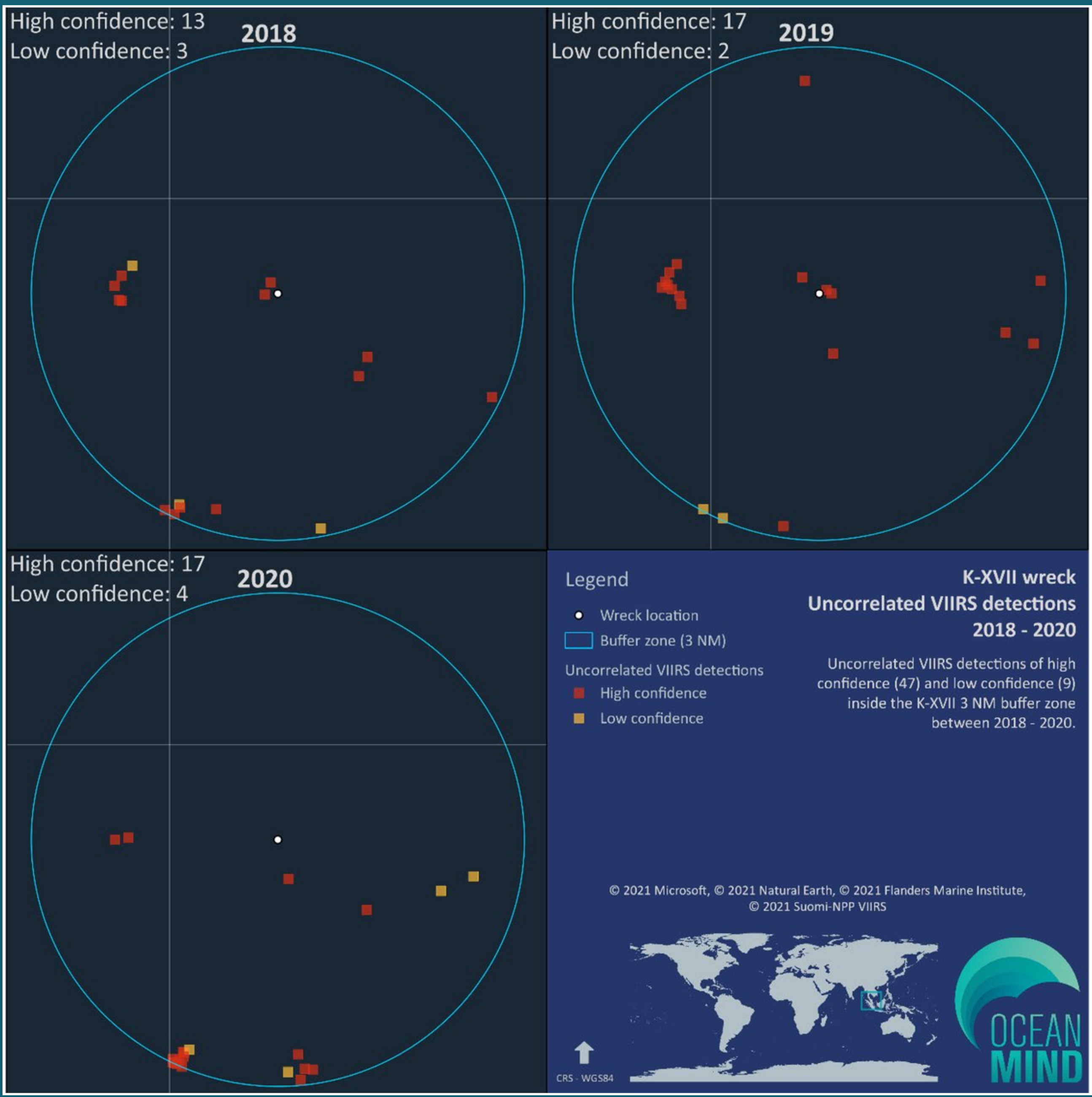


Figure 8

VIIRS data collected within a 3 NM buffer zone of a wreck in S E Asia. These are aggregated annual totals. Detections in 2018 and 2019 may indicate multiple instances of "dark" vessels operating over the wreck at night without transmitting on AIS. These could be the deck lights of squid fishing vessels, or salvage operations targeting the site. Further investigation would be required to determine the risk posed (Maritime Observatory).

Figure 9

Four examples of vessels monitored via AIS illustrate the diverse pattern of maritime activity in the Egadi MPA.

SMS Sulzbach-Rosenberg (Naval Operations)

Sea Cloud II (Cruise Ship)

Gianni M (High Speed Ferry)

Eco One (Oil and Gas Exploration)

Behavioural Models

Analysis of Risk Interactions

Risks to UCH can be broken down by vessel activity, which aids behavioural modelling. Six activity types were analysed within the Egadi MPA (Table 4). These broadly correspond to the AIS categories transmitted by vessels (see table for exceptions). Each type presents different types of potential threat to UCH, whether direct (e.g. diving, salvage, etc.) or indirect (e.g. anchoring, fishing, etc.).

Table 4. Risk interactions by vessel type

Vessel types	Possible risk activities
Cargo and passenger	Large vessels can damage wrecks by anchoring over a site. Even when an anchor is not sited directly on a wreck a large area of the surrounding seabed may be scoured by the movement of the anchor chain as the vessel swings in the tide or wind.
Dredging and survey	Dredging activity in proximity to wrecks can damage the wreck and the integrity of the seabed. Seabed surveys can be used to locate wrecks in advance of salvage or diving activity. Data can be collected from a variety of vessel types, not all of which are clearly identified as survey vessels on AIS.
Fishing	Wrecks provide good habitats for sea life and support large populations of commercially important fish species. Fishing vessels operating close to a wreck can cause damage due to gear snagging on the site. Such incidents contribute to marine pollution, harm marine life and can endanger other vessels at sea.
Diving and salvage	Dive vessels frequently visit wrecks for recreational diving. A minority of divers cause harm by removing items. Diving can be conducted from a variety of vessel types, not all of which are clearly identified as dive vessels on AIS. Unauthorised or unlicensed salvage activity is a major threat and a single vessel has the potential to quickly damage or completely destroy a site. Such incidents may also harm the environment and marine life through the uncontrolled release of pollutants.
Pleasure vessels	Vessels categorised as 'Pleasure' are typically yachts and private motor vessels. Some diving vessels are also categorised as 'Pleasure'. Small vessels may anchor on wrecks, possibly causing damage.
Other vessels	Vessels categorised as 'Other' can fit into any of the above categories and therefore require identification to assess the potential risk to wreck sites. Within the AOI these included naval vessels, law enforcement, search and rescue craft, survey vessels, offshore support vessels, tugs and high-speed craft.

Risk-Linked Behaviour Indications – Methodology

The AIS tracks of the vessel types above can show distinct behavioural patterns. In turn, a methodology can be created to identify and predict vessel movements associated with each activity. Some of these behaviours can be used to train machine-learning software and generate automatic alerts in much the same way as OceanMind's alert software currently identifies different patterns of activity at sea. Some examples are given below:

Survey

Vessels looking for a wreck may be identified through a typical search pattern, which can range in scale from multi-day coverage of a large area (Figure 10), to a targeted search of a precise location when a wreck location is already roughly known. Searches are normally carried out through remote sensing using towed or hull-mounted sensors (sidescan sonar, multibeam). These may be conducted in advance of a planned diving or salvage operation. Increasingly AUV and ROV systems are used for surveys. These sub-surface operations can also be identified using AIS, but the exact pattern of activity will vary considerably depending on the survey strategy and type of system deployed. It is worth noting that the position of the parent vessel on the surface may not correspond to the location of the vehicle underwater, particularly in the case of AUV models that can operate independently for long periods of time and travel long distances while submerged. Examples of correlated AIS tracks from AUV and ROV operations are given in Figure 11 and Figure 12.

Diving

Small scale ad hoc recoveries usually involve divers using RIBs or small boats. The motive may be souvenir-hunting or recovery of portable artefacts for sale. Research suggests there is a wide range of activity. Many have admitted occasionally removing objects from wreck sites during recreational dives, regardless of legality. More organised targeting of specific wrecks by dive groups is less common and is generally conducted as a hobby with only a small percentage done expressly for profit. This level of looting is thus not easily detected or distinguishable from normal recreational diving.

Diving boats have comparatively limited range, usually operating within territorial waters. They may spend only a short time on site and have a limited recovery capacity. Nonetheless looting is hugely damaging to sensitive historical sites, and numerous examples exist of wrecks being ransacked in this way.[6] It is

6 Examples include: HMT *Bedfordshire*, *U-85*, *U-352* and *U-701*, targeted by US scuba divers in 2008, allegedly including the removal of skeletal remains. *SS Alert*, an Australian protected wreck located at 80m depth, found to have been stripped by technical divers in July 2019, and the prosecution of diver Vincent Woolsgrove in 2015 for 61 offences related to the unauthorised recovery of artefacts from wrecks on the UK south coast.

difficult for remote sensing to monitor this type of activity since small vessels are not required to transmit AIS, and only a few choose to. It can be most effectively policed on designated sites where a measure of control already exists. Monitoring may also rely on OSINT.

Salvage

Salvors typically break a wreck apart to reduce the structure to manageable chunks for recovery. This can require lengthy periods of time at anchor over the site, easily detected on AIS tracks (Figure 14). Divers may use explosives or heavy machinery (chisels, grabs etc) to rip open the wreckage. Recovery of objects from the seabed is the most difficult aspect and requires specialist lifting gear. Such equipment can be distinguished from fishing apparatus in high resolution EO imagery and few vessels carry it.

In coastal and inshore waters salvors may operate from purpose-built platforms or converted commercial vessels such as trawlers. At this level operators are professionals, equipped with a range of lifting and recovery gear and the ability to conduct expeditions hundreds of miles from their homeport. Targets are likely to be wrecks with a high value cargo or large non-ferrous components, although some operators have removed entire wrecks for sale as scrap. Such vessels normally have a limited cargo capacity and endurance so may be required to make multiple trips to a productive site. Some salvors remain over a location for only a few hours before returning to port, whereas others have spent over a year working the same site. Vessels may also remain in an area working multiple sites to maximise profit. This pattern is quite distinct from fishing or other maritime activity.

Some salvors have transitioned between unauthorised recoveries and legitimate engineering work and may operate as part of a network that includes support vessels and metal reprocessing plants. In recent high-profile cases, salvors have used the opportunity offered by legal wreck removal contracts to target nearby historic sites, removing large warship remains entirely from the seabed in as little as a few days (Richardson 2023). The rapid nature of this transition highlights the necessity of active real-time monitoring to prevent irreversible destruction of such sites and the detailed knowledge of salvage laws and permits required to identify unauthorised activity carried out by seemingly legitimate operators.

Offshore Salvage

Offshore salvage uses specialised vessels and equipment to recover material from deeper waters outside the capabilities and range of other salvors. Targets may be located beyond the continental shelf and in international waters where legal protections are weakest. Such companies typically use ROV based systems which may restrict the size and amount of material that can be recovered.

Figure 10

AIS track of a vessel carrying out a large area survey using side-scan or multibeam systems – each transit is approximately 25 NM (Maritime Observatory).

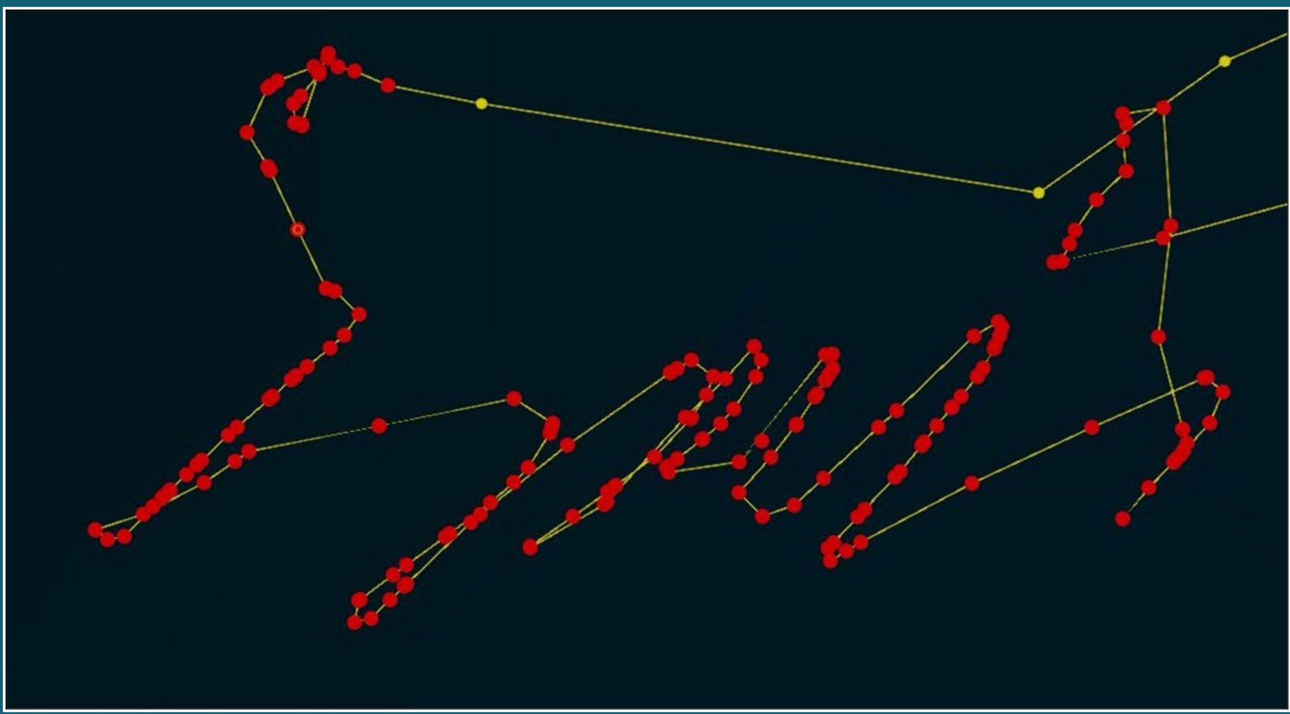


Figure 11

AIS track of a vessel carrying out AUV operations at the Egadi site. (Maritime Observatory).

Figure 12

AIS track of a vessel carrying out ROV operations at the Egadi site. Note there are 3 locations that were inspected on separate days. (Maritime Observatory).

Figure 13

AIS track of a small vessel carrying out authorised diving operations over a UK protected wreck, approximately 250m area (Maritime Observatory).

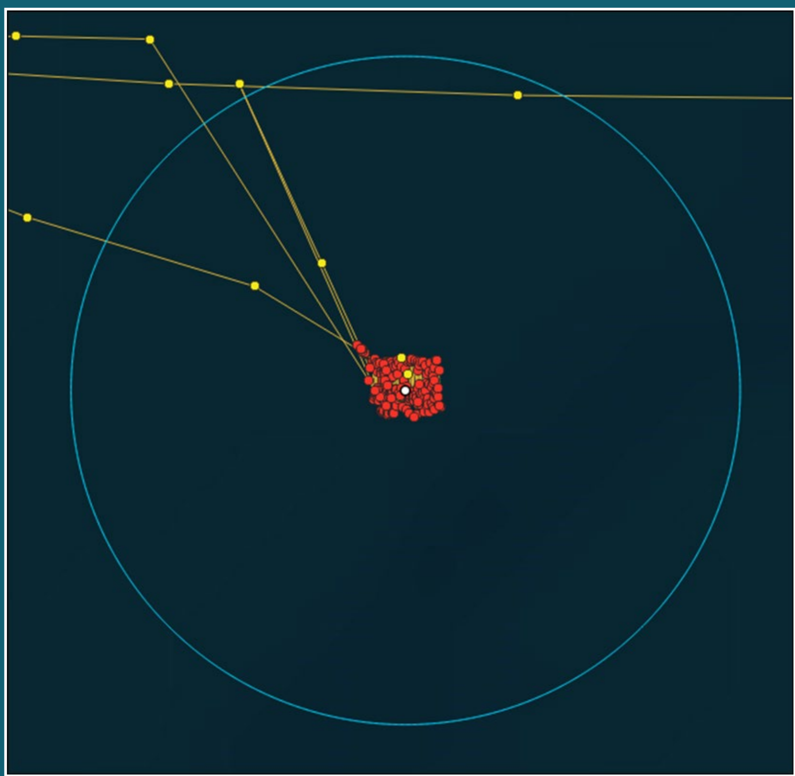
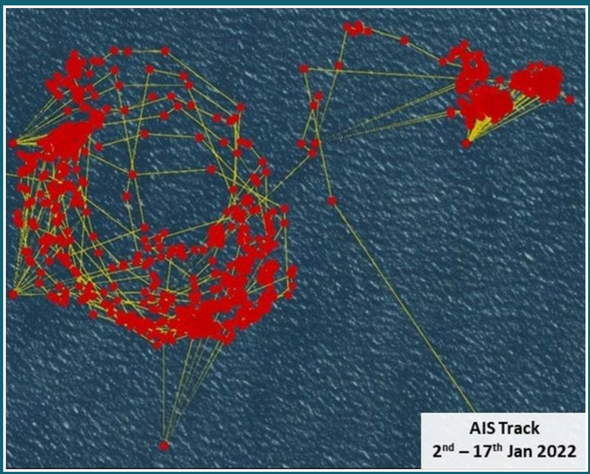


Figure 14

Typical AIS track data for a crane barge carrying out suspected dispersal and recovery operations on a target, with corresponding Sentinel-2 detection (Maritime Observatory).



Figures 15 and 16

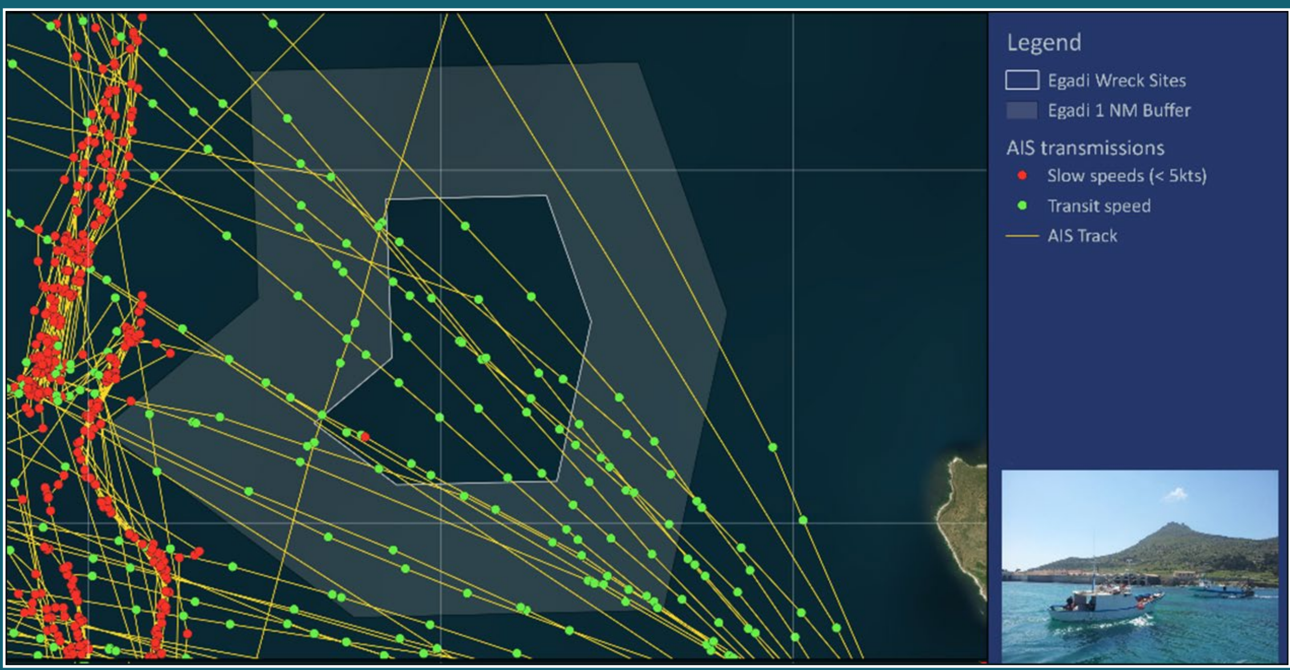
Left, FRIENDSHIP, a typical converted trawler, seen engaged in legitimate salvage work. (Source: friendship-offshore.com); right, HAI WEI GONG 889, a typical purpose-built salvage barge, photographed in 2013 with entire wreckage of illegally removed Netherlands submarine O-16 onboard. (Source: A local diver).

Figure 17

AIS track of a deep-water research vessel carrying out an authorised recovery operation over the Egadi Site (Maritime Observatory).

Figure 18

Example of a fishing vessel repeatedly transiting over the monitored area at speeds over 5 knots (Maritime Observatory).



Due to the increased costs of offshore work, salvors will typically only target high-value cargos. Previously many operators used their own dedicated vessels and equipment, but increasingly the trend is to hire commercial platforms such as oil and gas support vessels to carry out these operations. This can make identification of unauthorised salvage projects more difficult. The vessels are capable of long voyages to a worksite and can sustain long periods at sea. This pattern is quite distinct from fishing or other maritime activity.

Fishing

Fishing vessel operating too close to a wreck can cause significant damage from gear snagging on the site. During monitoring it is important to identify which fishing methods can be detected and the risks they represent to each site. Bottom trawling and scallop dredging are highly likely to endanger objects on the seabed in any location, while purse seine and long line fishing may pose a lesser risk to sites in deep water as the gear should not reach the bottom. Detailed knowledge of local laws and regulations may be required to identify unauthorised activity within a protected area as regulations vary between jurisdictions. In addition, it is important to distinguish vessels that are actively fishing from those simply transiting over an area. The Maritime Observatory classifies fishing vessels moving at speeds under 5 knots to be potentially fishing, while those moving at speeds over 5 knots are likely to be only transiting.

Dark Vessels

Inconsistencies in AIS data or turning off transmissions may indicate attempts to conceal potential illicit activity. However, identifying suspicious interference in an AIS track requires careful analysis as there can also be many innocent causes for signal interruption, including weak signal strength, inadequate satellite coverage and limited receiver capacity. Not every vessel is required to operate with AIS; since regulations vary by region and industry it is important to identify local AIS regulations during monitoring programmes.

Behavioural Observations Within the Egadi Islands MPA

It was clear from the AIS transmissions that the Egadi site lies below a busy stretch of water (Figure 9). In total 370 vessels were observed operating in the AOI and buffer zone during 2022. Table 5 divides these by category, area of operation and speed. (The total of 532 observations exceeds the total of 370 vessels since those that passed through both the AOI and buffer zone are counted in both respective columns.) *Pleasure* craft was the most frequently observed category, followed by *cargo*, *fishing*, and *passenger* vessels, with smaller numbers of *other* and just two *unknown*. Most vessels appeared only to be transiting across the AOI without interacting with it. This included all of the *cargo*, *hazardous cargo* and *unknown* vessels, and all but one of the *passenger* and *other* vessels.

Table 5. Total unique AIS identities by category

Vessel type	AOI: Speed <5 kts	AOI: Speed >5 kts	1 NM Buffer: Speed <5 kts	1 NM Buffer: Speed >5 kts	Total
Fishing	7	18	9	35	**69**
Cargo	0	15	0	34	**49**
Hazardous cargo	0	10	0	14	**24**
Passenger	1	34	0	10	**45**
Pleasure	21	79	44	167	**311**
Unknown	0	0	0	2	**2**
Other	1	11	1	19	**32**
Total	30	167	54	281	**532**

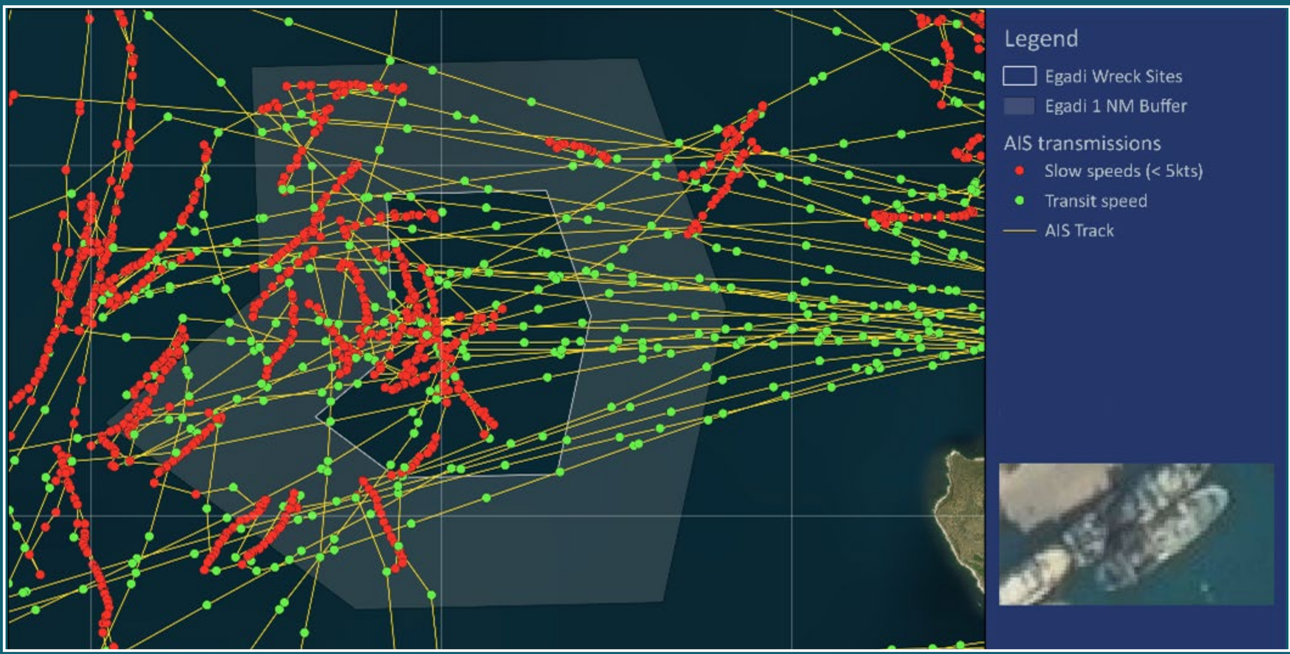
Thirty higher-risk vessels were observed in the AOI operating at speeds below 5 knots and a further 54 in the buffer zone. The AOI activity comprised seven *fishing* vessels, 21 pleasure craft, one *passenger* and one *other* (a research vessel).

The analysis revealed which of the seven fishing vessels were most active. One vessel was detected fishing inside the protected area on 33 separate occasions (Figure 19). In addition, 18 fishing vessels transited the AOI a total of 111 times during the year.

There is a seasonal pattern to the activity over the Egadi AOI (Figure 21). While the number of AIS identities associates with non-risk categories remains similar throughout the year, the number of fishing and pleasure craft is much higher between May and October (Figure 22). The number of pleasure craft peaked during August. However, the number of fishing vessels operating over the AOI in August was substantially lower than in surrounding months. One possible reason is the presence of the research vessel and the increased activity linked to the archaeological survey which may have deterred them. The only potential fishing activity detected in August was carried out when the research vessel was not there.

Figure 19

Example of a vessel actively trawling over the monitored area at speeds less than 5 knots (Maritime Observatory).



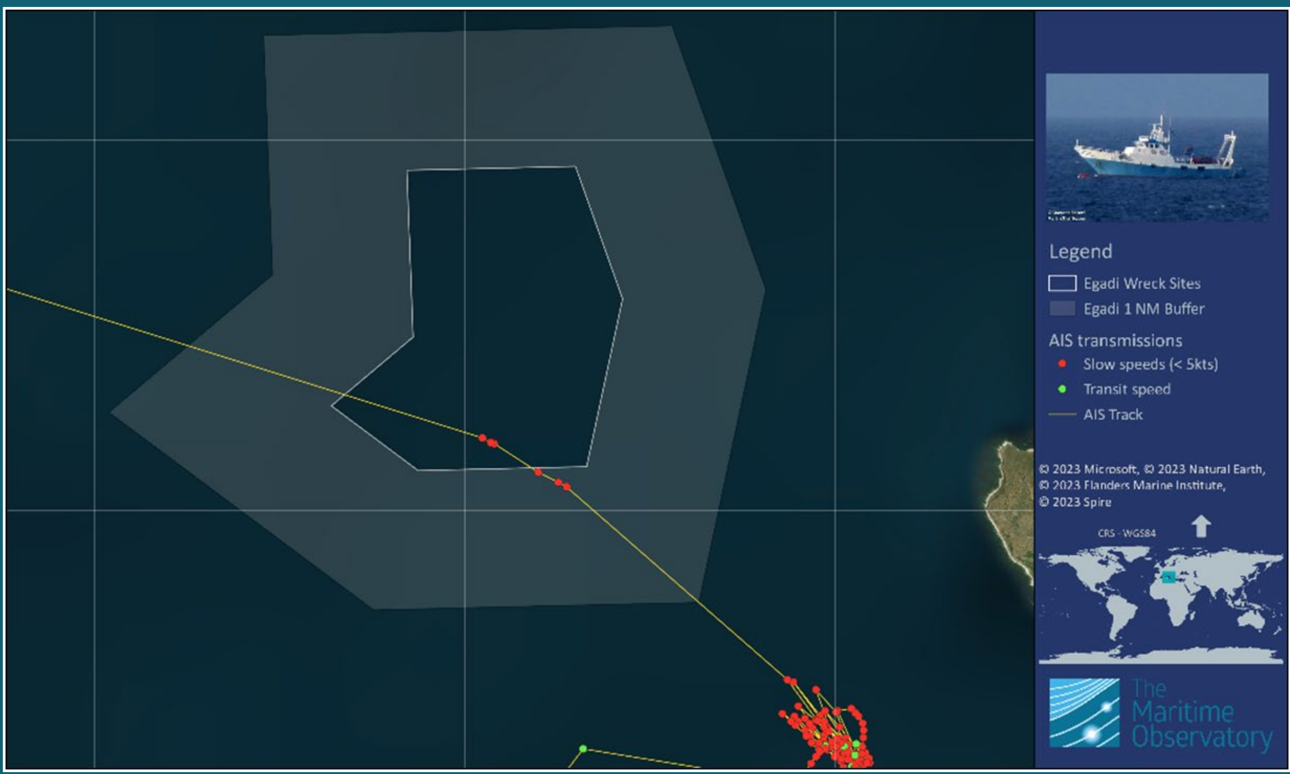


Figure 20

Example of a trawler's inconsistent AIS signal while operating at slow speed over the Egadi monitored area. This could be classified as an indicator of high-risk behaviour (Maritime Observatory).

Figure 21

A heatmap of AIS transmissions from vessels operating below 5 kts inside the Egadi MPA reveals the changing intensity of activity during the 12 month study period (Maritime Observatory).

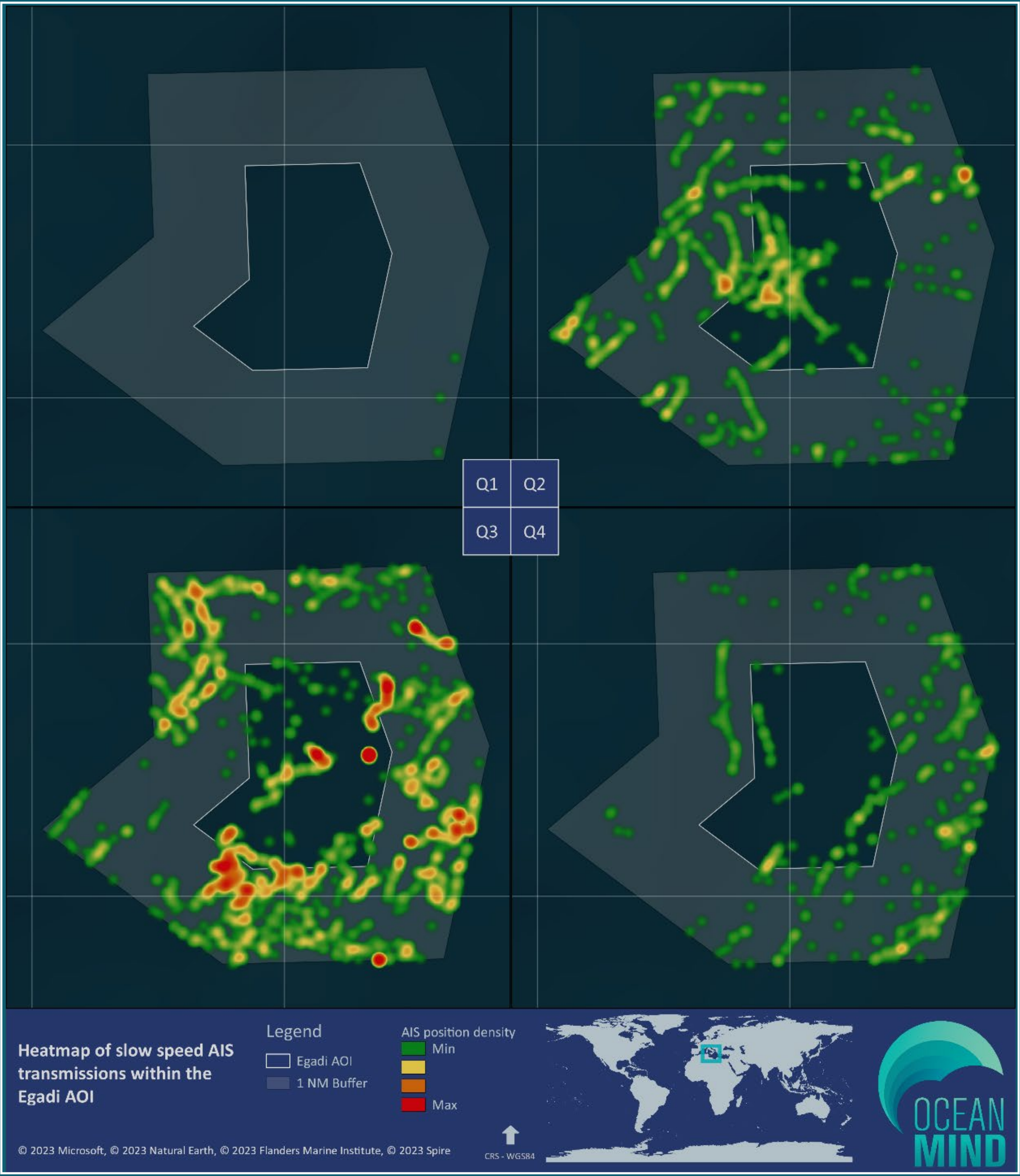
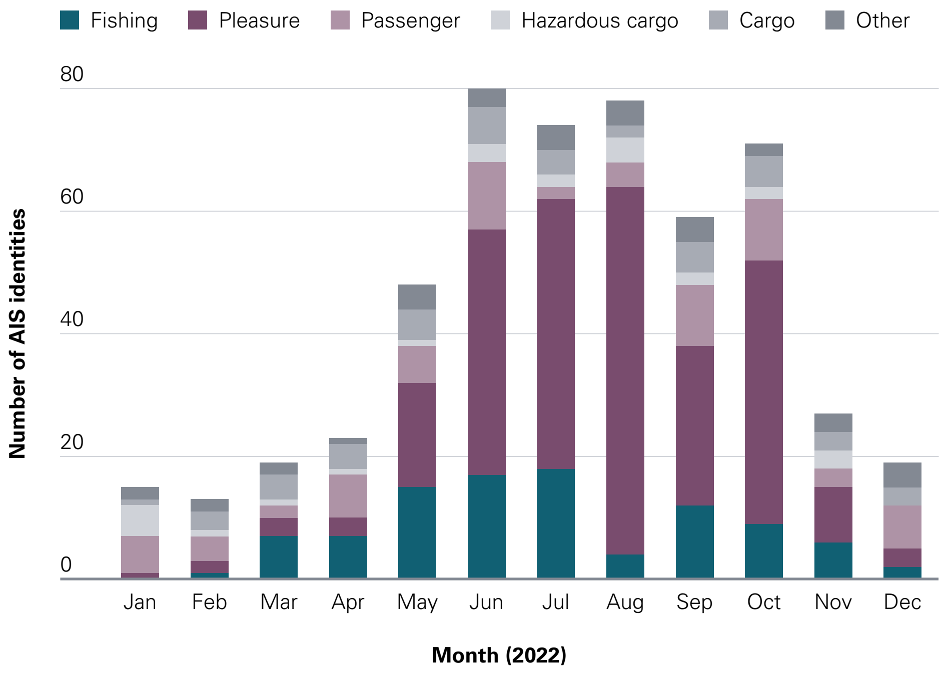


Figure 22. Number of AIS identities transmitting from within the Egadi AOI by month during 2022.



Vessel categories are colour coded by perceived risk (blue/purple scale) and no risk (grey scale).

By far the greatest risk appears to be from these trawlers, which have been proven to be actively fishing over the archaeological site between May and October (Figure 21). The small number of vessels involved (seven) may facilitate targeted engagement or deterrence by law enforcement to mitigate these risks to the site integrity.

Most vessel traffic appeared to transmit sufficiently on AIS to enable the movements to be monitored. However, the electro-optical and VIIRS analysis suggests that not all vessels which engage with the AOI transmit on AIS. 'Dark' vessels were frequently observed in the AOI with detections peaking in July and August. The total number of vessels operating over the AOI may therefore be higher than the AIS analysis suggests.

Investigating a Crime: Retroactive

An investigation into a possible heritage crime begins by identifying which sites have been affected. If activity or damage is witnessed on site this is straightforward, but if looted artefacts are discovered on a vessel, at a secondary location, or being smuggled across a border or airport, then this can be more complicated. Identifying the known UCH sites of the same time period and culture will narrow down the locations to target, though there is always potential that the material comes from a previously unknown site. Once the site or sites have been identified, then a retroactive satellite investigation can be undertaken.

Investigators should then consider the following for the sites identified:

1. What crime has occurred according to the legal code? The prosecution of the crime will follow the laws of the country you are operating in and will determine your 'research question'. Always be cognisant of the legal framework in order to gather relevant data and avoid superfluous analysis.

2. What data sources are required to identify the criminal activity? E.g. the theft of portable objects may only require a single dive and could be conducted from a RIB, while metal salvage could require days of intensive operations by a large vessel.

3. What bounds around the site do you require? The observation area should include the site as well as a buffer zone to identify the behaviour of vessels operating in the area (e.g. vessels in transit over a site versus turning off AIS when passing near the site). A one-kilometre buffer may be sufficient.

4. For what duration do you require data? Did the crime occur within a known timeframe (e.g. within the last 6 months) or has it been habitual (e.g. over the last 10 years)?

It is important to maintain records in case the analysis is required for a criminal investigation, and you are called as an expert witness in the court of law.

Creating a Monitoring System: Active

Heritage managers interested in creating a near real-time monitoring system should consider the following:

1. How many sites are you seeking to monitor? Sites located close together may be covered by the same satellite imagery at no extra acquisition cost, while those further apart may require two separate data sources.

2. What duration and what frequency of monitoring do you require to identify any criminal activity undertaken?

3. This need should be balanced against budget as datasets that are rapidly updated (e.g. daily, hourly) are likely to be more expensive than less regular updates (e.g. every 5 days).

4. What bounds around the site do you require (as above)?

While satellite AIS data may be acquired in near real-time, the time between acquisition and processing of satellite imagery may be several hours. Therefore, EO and SAR cannot be guaranteed to effectively assist live patrol support against a fast-moving craft within a maritime space. But insights can aid patrol planning to target crime ‘hot spots’. Using EO and SAR should significantly increase surveillance coverage compared to traditional patrols alone, and could be a cheaper option than deploying vessels in remote or inaccessible locations. Regular schedules could also inform historic and strategic assessments to assess the impact of maritime activity and potential risks to protected areas over time, particularly when combined with vessel tracking data. High risk areas or hot spots can then be targeted with other monitoring methods, such as UAVs to provide a more comprehensive picture of activity.

Conclusion

Heritage crime at sea is thriving. There is no single solution to protect UCH. But satellite monitoring is now increasingly accessible to archaeologists and law enforcement to monitor offences in real time or to investigate past crimes. This White Paper has sought to educate readers about the datasets and methods available, and how they can implement monitoring programmes in their own regions where expert local knowledge can be applied.

Readers are encouraged to get in touch with the Maritime Observatory to enquire about our monitoring services.

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References

Andreou, G., L. Blue, C. Breen, C. El Safadi, H.O. Huigens, J. Nikolaus, R. Ortiz-Vazquez & K. Westley. 2020. Maritime endangered archaeology of the Middle East and North Africa: the MarEA project. *Antiquity* 94. Cambridge University Press: e36. https://www.cambridge.org/core/article/maritime-endangered-archaeology-of-the-middle-east-and-north-africa-the-marea-project/E791D6A0B9C18D10A205C7A18202F16D. https://doi.org/DOI: 10.15184/aqy.2020.196.

Baeye, M., R. Quinn, S. Deleu & M. Fettweis. 2016. Detection of shipwrecks in ocean colour satellite imagery. *Journal of Archaeological Science* 66. Elsevier Ltd: 1–6. https://doi.org/10.1016/j.jas.2015.11.006.

Bass, G.F. 1966. *Archaeology Under Water*. London: Thames and Hudson.

Bradley, D., J. Bradley, M. Coombes, L. Grove, S. Thomas & C. Young. 2012. The extent of crime and anti-social behaviour facing designated heritage assets. https://www.sccjr.ac.uk/publication/the-extent-of-crime-and-anti-social-behaviour-facing-designated-heritage-assets.

Campbell, P.B., D.M. Smith, J.G. Royal, C.T. Begley, P. Zdravković & D. Irwin. 2018. Developing Maritime Archaeology Education and Outreach in the Balkans: The Illyrian Coastal Exploration Program's Field Schools in Albania, Croatia, and Montenegro, in K. Bell (ed.) *Bridging the Gap in Maritime Archaeology: Working with Professional and Public Communities*: 121–46. Oxford: Archaeopress.

Casana, J., D.D. Goodman & C. Ferwerda. 2023. A wall or a road? A remote sensing-based investigation of fortifications on Rome's eastern frontier. *Antiquity*. Cambridge University Press, 1–18. https://www.cambridge.org/core/article/wall-or-a-road-a-remote-sensingbased-investigation-of-fortifications-on-romes-eastern-frontier/8FE59FB0D5476EA329614EEC6DC414FD. https://doi.org/DOI: 10.15184/aqy.2023.153.

D'Anna, G., T.V. Fernández, C. Pipitone, G. Garofalo & F. Badalamenti. 2016. Governance analysis in the Egadi Islands Marine Protected Area: A Mediterranean case study. *Marine Policy* 71: 301–9. https://www.sciencedirect.com/science/article/pii/S0308597X15003796. https://doi.org/https://doi.org/10.1016/j.marpol.2015.12.009.

Fita, F. 1906. Inscripciones Griegas, Latinas y Hebreas. *Boletín de la Real Academia de la Historia* 48: 155–68.

Gross, M. 2018. Eyes on our planet. *Current Biology* 28: R89–92.

Keith, D.H. & T.L. Carrell. 2009. Going, Going, Gone: Underwater Cultural Resources in Decline BT – International Handbook of Historical Archaeology, in D. Gaimster & T. Majewski (ed.): 105–39. New York, NY: Springer New York. https://doi.org/10.1007/978-0-387-72071-5_7. https://doi.org/10.1007/978-0-387-72071-5_7.

Muckelroy, K. 1978. *Maritime Archaeology*. Cambridge: Cambridge University Press.

Office for National Statistics (ONS). 2024. Ship crossings through global maritime passages: January 2022 to April 2024. https://www.ons.gov.uk/businessindustryandtrade/internationaltrade/bulletins/shipcrossingsthroughglobalmaritimepassages/january2022toapril2024.

Parcak, S. 2019. *Archaeology from Space: How the Future Shapes Our Past*. New York: Holt.

Parcak, S., D. Gathings, C. Childs, G. Mumford & E. Cline. 2016. Satellite evidence of archaeological site looting in Egypt: 2002–2013. 188–205. https://doi.org/10.15184/aqy.2016.1.

Radić Rossi, I. 2014. Experience in current management of underwater cultural heritage in Croatia: The case of the protective cages. *Archaeologia Maritima Mediterranea* 11: 45–62.

Richardson, G. (2023). The Looting of HMS Prince of Wales & Repulse 2022-23. https://thisismast.org/maritime-observatory/chuan-hong-68.html.

Tusa, S., P. Campbell, M. Polakowski, W.M. Murray, F. Oliveri, C.A. Buccellato, A. Fresina & V. Li Vigni. 2021. The Battle of the Aegates Islands, 241 BC: mapping a naval encounter, 2005–2019, in C. Prescott, A. Karivieri, P. Campbell, K. Göransson & S. Tusa (ed.) *Trinacria, 'An Island Outside Time': International Archaeology in Sicily*: 167–79. Oxford: Oxbow.

Weekers, D., G. Petrossian & L. Thiault. 2021. Illegal fishing and compliance management in marine protected areas: a situational approach. *Crime Science* 10: 9. https://doi.org/10.1186/s40163-021-00145-w.

Westley, K. 2021. Satellite-derived bathymetry for maritime archaeology: Testing its effectiveness at two ancient harbours in the Eastern Mediterranean. *Journal of Archaeological Science: Reports* 38: 103030. https://www.sciencedirect.com/science/article/pii/S2352409X2100242X. https://doi.org/https://doi.org/10.1016/j.jasrep.2021.103030.

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