Chapter 1
Maritime Reporting Systems

Konstantina Bereta, Konstantinos Chatzikokolakis, and Dimitris Zissis

Abstract In recent years, numerous maritime systems track vessels while travelling across the oceans. Ship reporting systems are used to provide, gather or exchange information through radio reports. This information is used to provide data for multiple purposes including search and rescue, vessel traffic services, prevention of marine pollution and many more. In reality though researchers and scientists are finding out that these data sets provide a new set of possibilities for improving our understanding of what is happening or might be happening at sea. This chapter provides an introduction to the main vessel reporting systems available today, while discussing some of their shortcomings and strong points. In this context, several applications and potential uses are described.

1.1 Introduction

Unlike in the past, when tracking ships during their long voyages at sea was hampered by the lack of robust systems and data, nowadays numerous reporting systems are constantly reporting vessel positions. Today there are at least 23 mandatory commercial ship reporting systems, adopted by the International Maritime Organization (IMO) in accordance with the Safety of Life at Sea (SOLAS) regulation V/11 in the world. The SOLAS convention is a maritime treaty aiming at the establishment of safety specifications in the construction of vessels and the installation of equipment. Flag states are the states in which vessels are registered under their flag. Flag states should ensure that the vessels under their flag comply with the standards of the SOLAS convention.

K. Bereta (✉) · K. Chatzikokolakis
MarineTraffic, Athens, Greece
e-mail: konstantina.bereta@marinetraffic.com

K. Chatzikokolakis
e-mail: konstantinos.chatzikokolakis@marinetraffic.com

D. Zissis
University of the Aegean, Syros, Greece
e-mail: dzissis@aegean.gr

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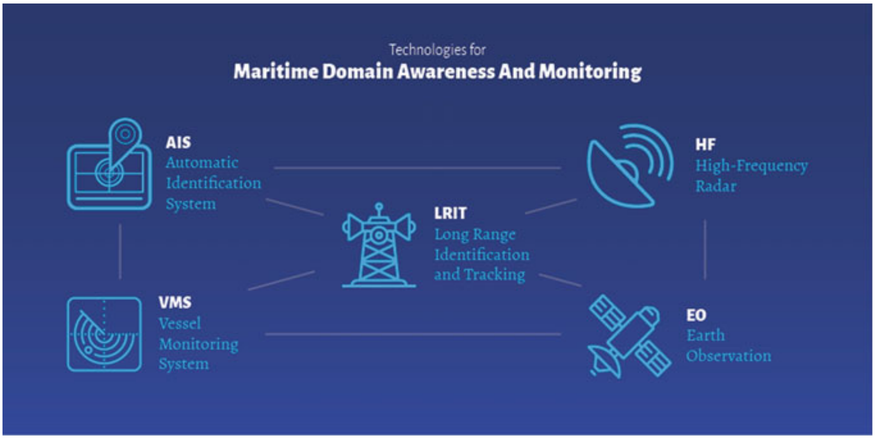

Fig. 1.1 Use of reporting systems for Maritime Situational Awareness

Figure 1.1 shows some of the vessel monitoring systems that are currently used to track vessels. In general, systems that can track vessels can be divided into two broad categories: cooperative and non-cooperative systems. Cooperative systems rely on the vessels crews' collaboration to identify and report the information about a vessel, while non-cooperative systems are designed to detect and track vessels that do not rely on the vessels crews' collaboration. Cooperative systems include the Automatic Identification System (AIS), the Vessel Monitoring System (VMS), the Long Range Identification and Tracking (LRIT) system, and others. Non-cooperative systems on the other hand, include coastal and high-frequency (HF) radar, active and passive sonar, ground- or vessel-based cameras (e.g., thermal), and satellite and airborne Earth Observation (EO) systems. EO systems can be divided into optical (generally visual and near-infrared) and Synthetic Aperture Radar (SAR) systems. Yet, despite the variety of tracking systems available and the massive data flows they produce, the "views" obtained by such data remain largely partial. In this context, data fusion is critical as it combines multi-origin information to determine relationships among the data; thus improving the understanding of a current complex environment. The advantage in fusing data from multiple sensors and sources is that the final estimated vessel trajectories are more accurate and with better confidence, extending to features that are impossible to perceive with individual sensors and sources, in less time, and at a lower cost. Also, it contributes towards better coverage and robustness to failure, thus improving the reliability and quality of the situational picture.

In this chapter we describe the most popular reporting systems, including those that are currently being developed and are expected to be used in the future. This chapter is intended for readers who wish to begin research in the field of maritime information systems. As such, emphasis is placed on a description of the available reporting systems, their technical details, produced datasets, while references are provided for further information. Some examples are provided as to how these datasets can offer insights into shipping patterns.

This chapter is organised as follows. Section 1.2 describes the Automatic Identification System (AIS). Section 1.3 describes VHF Data Exchange System (VDES) and Sect. 1.4 describes the Long Track Identification and Tracking system. Section 1.5 describes the Vessel Monitoring System for fisheries and Sect. 1.6 describes advanced applications that rely on data that derive from vessel reporting systems. Finally, Sect. 1.7 concludes the chapter and Sect. 1.8 presents some bibliographical notes.

1.2 The Automatic Identification System

The Automatic Identification System (AIS) was originally conceived as a navigational safety system to support vessel traffic services (VTS) in ports and harbours, but soon after its adoption, and especially after the International Maritime Organization (IMO) mandated AIS transceivers to be installed on-board a significant number of commercial vessels, it became the most popular vessel tracking system.

The Automatic Identification System [13] allows for efficient exchange of navigational data between ships and shore stations, thereby improving safety of navigation. Although this system was intended to be used primarily for safety of navigation purposes in ship-to-ship use (e.g., prevention of collisions), it may also be used for other maritime safety related communications, provided that the primary functions are not impaired; the system is autonomous, automatic, continuous and operates primarily in a broadcast. The system automatically broadcasts navigational information about vessels along with vessel characteristics (e.g., name) to all other installations (e.g., AIS stations, on-board transceivers) in a self-organized manner. Data transmissions are made in the VHF maritime mobile band. Since its introduction, AIS data has proven useful for monitoring vessels and extracting valuable information regarding vessel behaviour, operational patterns and performance statistics.

In the rest of this section, we briefly describe the AIS communication protocol, provide detailed analysis of the information broadcasted through the AIS including sample datasets and argue on the common issues and shortcomings of AIS.

1.2.1 AIS Equipment

AIS is based on the use of dedicated equipment that should be installed aboard (vessel stations), ashore (base stations) or on dedicated satellites (AIS-SAT). Vessels are equipped with transponders, e.g., stations that send and receive AIS messages. Transponders can either be class A or class B and have an integrated GPS that tracks the movement of the vessel it is installed on. The differences between class A and class B transponders will be presented in the next section. Base stations that are installed ashore are equipped with AIS receivers that receive AIS messages from vessels, but do not transmit. Dedicated satellites are also equipped with AIS receivers and this is very useful for areas with no or low coastal coverage (i.e., with no AIS receiver nearby).

Since 2004, the International Maritime Organization (IMO) requires that all commercial vessels over 300 Gross Tonnage (GT) travelling internationally to carry a Class A AIS transponder aboard. Vessels that do meet these requirements (e.g., smaller vessels, pleasure crafts, etc.) can be equipped with Class B AIS transponders. This requirement of IMO followed the 2002 SOLAS (Safety of Life at Sea) agreement's relative mandate.

AIS transponders use two dedicated VHF channels, AIS-1 (161.975 Mhz) and AIS-2 (162.025 Mhz). Class A transponders implement the Self Organizing Time Division Multiple Access (SOTDMA) protocol. The SOTDMA protocol is based on the division of time in slots. More specifically, a second is divided into 2250 slots, which means that base stations can receive at most one transmission every 26.67 ms. Each vessel should reserve a dedicated time slot in order to transmit an AIS message so that no other vessel transmits at the same time.

Class B transponders use the CSTDMA (Carrier Sense Time Division Multiple Access) protocol which interweaves with Class A transmissions by giving priority to SOTDMA transmissions.

1.2.2 AIS Messages

The ITU 1371-4 standard defines 64 different types of AIS messages that can be broadcast by AIS transceivers. These include Types 1, 2, 3, 18, and 19 which are position reports, including latitude, longitude, speed-over-ground (SOG), course-over-ground (COG), and other fields related to ship movement; while type 5 messages contain static-and-voyage information, which includes the IMO identifier, radio call sign (e.g., a unique designation for each radio station), ship name, ship dimensions, ship and cargo types. Other types of messages include supplementary information about the vessel and are not needed for monitoring the vessels' mobility, thus are not further described in this chapter.

AIS messages are distinguished on the following two categories: (i) dynamic, and (ii) static. Dynamic messages contain positional data about voyages. Static messages contain information related to vessel characteristics. The information (e.g., flag) changes less frequently than the respective information included in static messages. The information contained in both types of AIS messages is described below.

1.2.3 Dynamic AIS Messages

The dynamic AIS messages contain the following attributes:

- *Maritime Mobile Service Identity Number (MMSI)*. The MMSI is an identification number for each vessel station. However, it is not a unique identifier, as we will explain later in this chapter.
- *Rate of Turn*. This field contains data regarding the angle that the vessel turns right or left per minute. The values of this field range from 0 to 720 degrees.
- *Speed over Ground*. Speed over ground is the speed of the ship with respect to the ground. The value range of this attribute is from 0 to 102 knots (0.1-knot resolution).
- *Position Coordinates*. This field contains the latitude and the longitude of the position of the vessel.
- *Course over Ground (COG)*. COG describes the direction of motion with respect to the ground that a vessel has moved relative to the magnetic north pole or geographic north pole. The values are degrees up to 0.1° relative to true north.
- *Heading*. Heading describes the direction that a vessel is pointed at any time relative to the magnetic north pole or geographic north pole. Heading takes values from 0 to 359 degrees.
- *UTC seconds*. This is the second part of the timestamp when the subject data-packet was generated (in UTC time).
- *AIS Navigational status*. This field represents the navigational status of the vessel and it is completed manually by the crew. The different types of navigational status that can be reported in an AIS message are the following:
    - *Under way using engine*: the vessel is travelling using its engine.
    - *Anchored*: The vessel is not travelling and has dropped an anchor.
    - *Not under command*: The vessel is uncommanded. This can be either due to a hardware malfunction or a problem of the crew (e.g., the commander is injured).
    - *Restricted maneuverability*: There are constraints regarding the motion of the vessel (e.g., tugging heavy load).
    - *Constrained by her draught*: The draught (or draft) of a vessel is the vertical distance between the waterline and the bottom of the hull (keel). The draught is an indicator that shows how much a vessel is loaded. So, a vessel carrying heavy load might have maneuverability restrictions (e.g., navigating in shallow waters).
    - *Moored*: The vessel is moored at a fixed point (e.g., dock).
    - *Aground*: The vessel is touching the ground, after navigating in shallow water.
    - *Engaged in fishing activity*: The vessel is currently fishing.
    - *Underway sailing*: The vessel is travelling using sails instead of engine (it applies to sailing vessels).
    - AIS-SART (active), MOB-AIS, EPIRB-AIS. The AIS-SART is a self-contained radio device used to locate a survival craft or distressed vessel by sending updated position reports. MOB-AIS are personal beacons with an integrated GPS that can be used by a shipwrecked person to transmit a “Man Overboard” alert in order to be tracked by rescue services. The Emergency Position Indicating Radio Beacon (EPIRB) is installed on vessels to facilitate the search and rescue operations on case of emergency. Every EPIRB is registered through the

national search and rescue organisation associated to the vessel is installed on. In case of emergency, it is manually or automatically (e.g., when it touches the water) activated sending distress signals (e.g., emergency alerts) through AIS. These signals are received by the search and rescue services that are closer to the area of the accident.

Apart from the navigational status values described above, there are also values that are reserved for future use. For example, there is a placeholder for future amendment of navigational status for ships carrying dangerous goods (DG), harmful substances (HS), marine pollutants (MP) or IMO hazard or pollutant categories, high-speed craft (HSC), and wing in ground (WIG).

1.2.4 Static AIS Messages

Static information is provided by a subject vessel's crew and is transmitted every 6 min regardless of the vessel's movement status. The static AIS messages contain the following fields:

- *International Maritime Organisation number (IMO)*. This is a 9-digit number that uniquely identifies the vessel. Please note that this is not the same as the MMSI. The IMO number is assigned by IHS Maritime (Information Handling Services) when the vessel was constructed.[1] The MMSI can change, for example when the owner changes. Only propelled, seagoing vessels of 100 gross tons and above are assigned an IMO number.
- *Call Sign*. The international radio call sign assigned to the vessel by her country of registry.
- *Name*. The name of the vessel.
- *Type*. The type of the vessel (e.g., Tanker).
- *Dimensions*. Dimensions of ship in meters. More specifically, this field refers to: (a) dimension to bow, (b) dimension to stern, (c) dimension to port (left side of the vessel when facing the bow), and (d) dimension to starboard (i.e., right side of the vessel when facing the bow).
- *Location of the positioning system's antenna on-board the vessel*.
- *Type of positioning system (GPS, DGPS, Loran-C)*. Differencial GPS (DGPS) is a positioning system that performs positional corrections to GPS, providing more accurate positioning data. Loran-C (Long-range navigation) is a hyperbolic radio navigation system that allows a receiver to determine its position by listening to low frequency radio signals transmitted by fixed land-based radio beacons. Although Loran-C system is old, it can be used as backup system to the GPS, since GPS can be spoofed or jammed.

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[1] https://ihsmarkit.com/products/imo-ship-company.html.

- *Draught*. The term draught (or draft) refers to the vertical distance between the waterline and the bottom of the hull (keel), with the thickness of the hull included. The value of this field is measured in meters.
- *Destination*. The destination as completed manually by the crew of the subject vessel (free text).
- *Estimated time of arrival (ETA)*. This is a UTC timestamp completed manually by the crew indicating the estimated time of arrival at destination.

There are some differences exchanged between vessels with class A and class B transponders, as shown in Table 1.1. For example, most of the vessels for which it is not mandatory to have class A transponders do not have an IMO, so this attribute is not used in messages sent from class B transponders. Rate of turn, navigational status, destination and ETA reports are also attributes that are not used in Class B AIS messages. Also, vessels with class B transponders do not transmit but are able to receive AIS messages related to safety.

Tables 1.2, 1.3, and 1.4 describe the reporting rates of vessels with class A and class B transponders. The AIS reporting rates of vessels depend on their navigational status (e.g., whether they are underway using engine or moored), their speed and course changes, and whether they are quipped with class A or class B transponders. Both class A and class B vessels that are anchored/moored or move very slow (up to 2 knots) send AIS messages every 3 min. Class B vessels with speed more than 2 knots send messages every 30 s, while class A have higher reporting rate that increases as the vessel accelerates and/or it is changing course. For example, a class A vessel that navigates with speed up to 14 knots needs to send AIS messages every 10 s.

1.2.5 Example Dataset

We provide example AIS messages through sample data of a dataset that is publicly available.[2] Table 1.5 shows a sample of static AIS messages (as the ones presented in Sect. 1.2.4 above) that contains the following attributes: MMSI, IMO, Call sign, Name, Type (the code corresponding to the vessel type), Dimension to bow, Dimension to stern, Dimension to port, Dimension to Starboard, Estimated arrival time (ETA), Draught, Destination, and the timestamp when the AIS message was received by an AIS receiver (e.g., terrestrial, satellite, or an AIS transceiver installed aboard the vessel). It is apparent from the table that some fields may be missing in some messages (e.g., destination in messages 2 and 4), or invalid in other (e.g., draught reported in messages 2 and 4). Table 1.6 depicts sample dynamic AIS messages from the same dataset. The dynamic messages contain the following attributes: MMSI, the code that corresponds to the navigational status of the vessel, the rate of turn, the speed over ground, the course over ground, the heading, the location of the vessel (longitude and latitude dimensions), and the timestamp.

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[2] https://zenodo.org/record/1167595#.XQtPIY9RUuU.

Table 1.1 Attributes of AIS messages exchanged using Class A and Class B transponders [13]

Data	Class A (receive)	Class B (send)	Class B (receive)
Call sign	Yes	Yes	Yes
IMO	Yes	No	No
Length and beam	Yes	Yes	Yes
Antenna location	Yes	Yes	Yes
Draught	Yes	No	No
Cargo information	Yes	Yes	Yes
Destination	Yes	No	No
Estimated time of arrival	Yes	No	No
Time	Yes	Yes	Yes
Ship's position	Yes	Yes	Yes
Course over ground	Yes	Yes	Yes
Speed over ground	Yes	Yes	Yes
Gyro heading	Yes	Yes	Yes
Rate of turn	Yes	No	No
Navigational status	Yes	No	No
Safety message	Yes	No	Yes

Table 1.2 Class A systems

Ship's dynamic conditions	Reporting rate
Anchored/Moored	3 min
0-14 knots	10 s
0-14 knots and changing course	3.33 s
14-23 knots	6 s
14-23 knots and changing course	2 s
Faster than 23 knots	2 s
Faster than 23 knots and changing course	2 s

Table 1.3 Class B systems

Ship's dynamic conditions	Reporting rate
0-2 knots	3 min
Above 2 knots	30 s

Table 1.4 Other AIS sources

Special conditions	Reporting rate
Search and Rescue (SAR) aircraft	10 s
Aids to navigation	3 min
AIS base station	10 s or 3.33 s

Table 1.5 Example of static AIS messages

MMSI	304091000	228037600	228064900	227705102
IMO	9509255	0	8304816	262144
Call sign	V2GU5	FIHX	FITO	FGD5860
Ship name	HC JETTE-MARIT	AEROUANT BREIZH	VN SAPEUR	BINDY
Ship type	70	30	51	60
To bow	130	6	21	9
To stern	30	9	54	26
To starboard	18	5	10	5
To port	6	2	6	4
ETA	04-09 20:00	00-00 24:60	29-09 12:00	00-00 24:60
Draught	10.1	0	5.9	0
Destination	BREST		RADE DE BREST	
Time	1443650423	1443650457	1443650471	1443650474

Table 1.6 Example of dynamic AIS messages

MMSI	245257000	227705102	228131600	228051000	227574020
Navigational status	0	15	15	0	15
Rate of turn	0	−127	−127	−127	−127
Speed over ground	0.1	0	8.5	0	0.1
Course over ground	13.1	262.7	263.7	295	248.6
Heading	36	511	511	511	511
Longitude	−4.4657183	−4.4965715	−4.644325	−4.4851084	−4.4954414
Latitude	48.38249	48.38242	48.092247	48.38132	48.38366
Time	1443650402	1443650403	1443650404	1443650405	1443650406

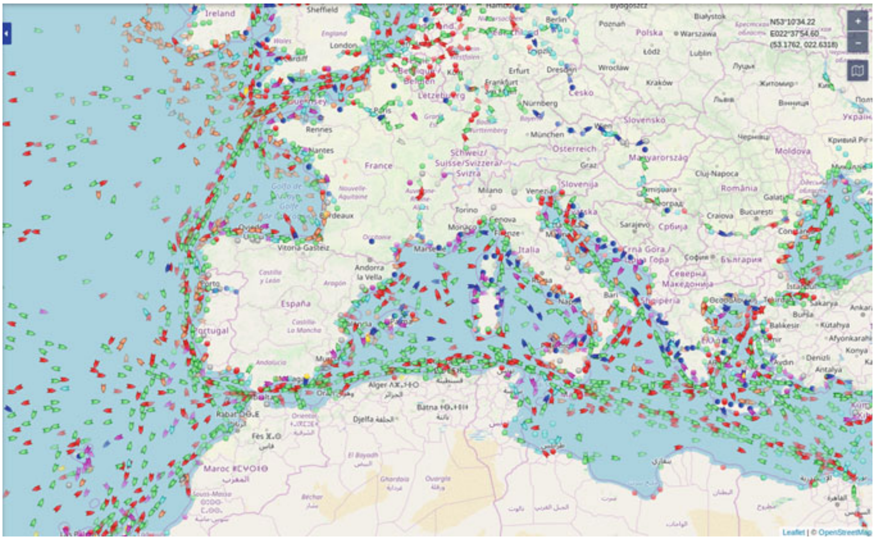

Fig. 1.2 Density maps layer of MarineTraffic's services

1.2.6 AIS Processing Difficulties and Challenges

The Automatic Identification System was initially designed to allow vessels to provide ship information automatically to other ships in the vicinity and to maritime authorities. The aim was to assist vessel's officers on the watch and coastal authorities to track maritime traffic and thus, reduce collision risk and improve the overall safety at sea. With the vast proliferation of vessel tracking systems, AIS has been used for vessel tracking services at a global scale. Such systems collect streams of AIS messages transmitted from the world's fleet and provide global ship tracking intelligence services such as those of MarineTraffic.[3] Figure 1.2 illustrates the density map of vessel traffic and highlights one of the capabilities the AIS tracking systems can offer.

However, since the initial purpose of the AIS communication system was not tracking vessels and their activities globally, some inherent characteristics of the communication protocol raise technical challenges that should be addressed to offer consistent and reliable information.

1. **Absence of unique ship identification**. Dynamic AIS messages (presented in Sect. 1.2.3) include the MMSI and IMO fields. The IMO number is a unique identifier for ships, registered ship owners and management companies that cannot be modified but is not mandatory for all the vessels. In fact, SOLAS regulation XI/3 made IMO number mandatory for all cargo vessels that are at least 300 Gross Tons (GT) and passenger vessels of at least 100 GT [13]. Vessels solely engaged

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[3] https://www.marinetraffic.com/.

in fishing, ships without mechanical means of propulsion and pleasure yachts are just some examples of vessel types that are not obliged to have an IMO number. On the other hand, MMSI is a nine-digit number that is mandatory for all the vessels, but it is not a unique identifier (i.e., it can be modified under certain circumstances) [13]. According to ITU,[4] the first 3 digits of any MMSI number are called Maritime Identification Digits (MID) and indicate the respective vessel's flag. Thus, when a vessel owner decides to change the flag under which the vessel will sail, her MID will be updated and consequently her MMSI will change. The absence of a global unique ship id for all the vessels of the world fleet, dictates the necessity to parse the received AIS data, clean the stream from messages with invalid MMSI identifiers and assign a unique id to the rest of them before proceeding with any further processing.

2. **Prone to human errors**. Some of the information included in AIS messages are manually inserted by the vessel's crew. The reported destination and the Estimated Time of Arrival (ETA) are typical examples of inconsistent and unreliable information reported through AIS. For instance, a passenger vessel that is performing the same itinerary with multiple stops every day, may not change the destination for each stop and report only the final destination from the beginning of the voyage. Furthermore, "Piraeu", "Piraeus Port", "Piraeus Anchorage", "Pir", "P" are all acceptable values in the reported destination of a vessel travelling to the port of Piraeus. String similarity metrics can be used to deduce the correct destination. Similarly, the ETA field is also prone to errors as it may not correspond to the time needed to reach the next port but the time needed to reach the final destination. Manually inserted information is not reliable and data processing of AIS stream would provide more accurate results. For instance, calculating the ETA based on the vessel's speed or determining the vessel's destination based on its itinerary history or using pattern-of-life analysis [4] would provide more reliable information.

3. **Reporting Frequency**. According to the AIS communication protocol the reporting intervals are fluctuating and depend on the vessel's behaviour (e.g., speed, rate of turn). This decision was taken so as to avoid throttling the system with too many messages that would lead to packet collision and message re-transmission, but at the same time transmit frequent messages when moving with high speed or changing course so as to notify in time other vessels in the vicinity. From the data provider perspective the reception rate is the same as the vessel's transmission rate when the vessel is in range of a terrestrial station (which is approximately 50 km), but can be significantly lower when the vessel is sailing at open seas. In such case the satellites are used for monitoring and the update interval may range from few minutes up to several hours, depending on the satellite availability. All these lead to non-uniform distribution of collected data with significant communication gaps in some cases that may lead to inaccurate trajectory construction.

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[4] https://www.itu.int/en/ITU-R/terrestrial/fmd/Pages/mid.aspx.

4. **Sensor malfunction**. It may occur that a vessel is transmitting erroneous information due to sensors' faulty operation. To discard such messages from the AIS data stream, feasibility analysis is essential to evaluate whether a vessel position is valid based on the vessel's past positions.

5. **Timestamping**. The only time-related information included in AIS messages is the seconds field of the UTC timestamp at which the AIS message was generated, as mentioned in Sect. 1.2.3. This is sufficient information for the vessels in the surrounding area, but when it comes to ship tracking data providers that store AIS messages for historical analysis, each message should be time referenced. This is usually done by assigning the UNIX epoch (i.e., seconds elapsed since 01/01/1970) the moment each message is collected in base station. When the messages are aggregated in a central entity from the receivers, processing is needed to avoid duplicate messages (i.e., messages that were received from more than one station). Furthermore, it is likely that the messages arrive with a variable delay. This may be caused by network delay or due to collecting data from various sources (terrestrial stations or satellite-AIS stations) that may be out of synch. Message re-ordering or accepting messages with a delay in the stream system would tackle such issue.

1.2.7 AIS Applications & Use Cases

There is a growing body of literature on methods for exploiting AIS data for safety and optimisation of seafaring, namely traffic analysis, anomaly detection, route extraction and prediction, collision detection, path planning, weather routing and many more.

The work described in [20] introduces a method that identifies fishing activities using AIS. The method uses AIS messages transmitted within an area of interest and after some analysis tasks performed, such as the construction of the speed profile of vessels, a map is produced that shows all fishing activities of the EU fleet in high spatial and temporal resolution. In a similar direction, the work described in [18] describes a big data approach that uses AIS data in large scale to identify port operational areas. More specifically, the paper proposes an implementation of the Kernel Density Estimation (KDE) algorithm using the MapReduce paradigm and applies it on large volumes of AIS data for a specific area of interest (i.e., a busy seaport), identifying activity areas suggesting port operations. The work described in [27] presents another big data approach used for the extraction of global trade patterns. In particular, AIS data are used for the extraction of routes, e.g., port-to-port voyages categorized by ship type. Routes are constructed for each combination of port of departure, port of arrival, and ship type from AIS messages using MapReduce. Then, each set of voyages belonging to the same route per ship type are clustered using K-Means. K-Means is a clustering algorithm that is based on the idea that n elements are clustered into k groups, with each element belonging to the group with the nearest mean.

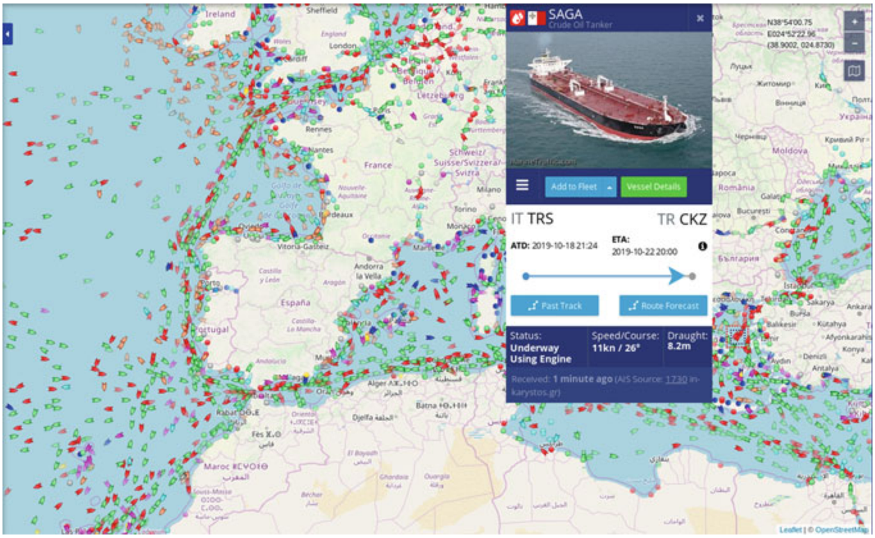
SAGA
Crude Oil Tanker
IT TRS
TR CKZ
ATD: 2019-10-18 21:24
ETA: 2019-10-22 20:00
Status: Underway Using Engine
Speed/Course: 11kn / 26°
Draught: 8.2m
Received: 1 minute ago (AIS Source: 1730 in-karystos.gr)
N38°54'00.75 E024°52'22.96 (38.9002, 024.8730)

Fig. 1.3 Snapshot of the MarineTraffic Live Map showing the current positions of vessels and other data based on AIS messages

Since AIS was initially developed to assist in collision avoidance, soon after its establishment the first approaches for automatic detection of collisions emerged. A highlight of these approaches is for example the work described in [19], presenting an approach for collision avoidance in busy waterways by using AIS data.

The work described in [20] introduces the development of a framework that performs anomaly detection and route prediction based on AIS data. More specifically, it presents an unsupervised and incremental learning framework, which is called TREAD (Traffic Route Extraction and Anomaly Detection) for the extraction of movement patterns aiming at automatically detecting anomalies and projecting current trajectories and patterns into the future. In the context of anomaly detection, one common anomaly in the maritime domain is *spoofing*, which happens when a vessel attempts to camouflage her identity using the identification codes and/or the name of another vessel to hide her whereabouts. This might happen due to human error or on purpose, i.e., when the vessel is engaged in illegal activities and attempts to “hide” its identity. The work described in [17] introduces a big data approach that identifies spoofing events on AIS data streams.

Another interesting topic is the identification of events in the maritime domain. For example, the work documented in [23] proposes a rule-based system that uses Run-Time Event Calculus in order to perform recognition of complex events.

An interesting application that relies mainly on AIS data concerns MarineTraffic services. Figure 1.3 is an illustration of the MarineTraffic Live Map displaying the most recent positions of all vessels with active AIS transponders. Different colours correspond to different vessel types. Once a user clicks on a the position of a vessel

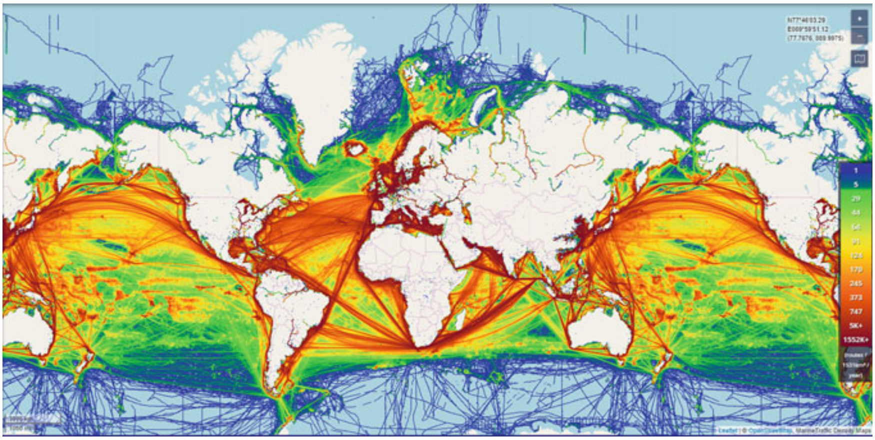

Fig. 1.4 Details of a vessel as derived from MarineTraffic's processing and analysis of AIS messages

on the Live Map, she is able to see some additional details about the vessel and its current voyage. For example, Fig. 1.4 shows the thumbnail of a photo showing a tanker named "SAGA", its type, its latest position and navigational status, destination, speed and draught. This information is made available after processing AIS messages transmitted by the vessel. The estimated time of arrival (ETA) to the reported destination is also displayed, but this derives from the analysis of AIS data related to the voyage (e.g., latest position, distance to the destination, speed, etc.).

1.2.8 Applications of AIS in the Book

The remaining chapters of this book present solutions regarding different aspects of processing, visualising, and analysing AIS data, as well as interesting applications that are based on AIS data.

The first part of the book describes maritime data. Tzouramanis [29] provides an overview of open maritime datasets, including a detailed list of the different sources of AIS data, and open datasets that could be used to enrich the information contained in vessel tracking data. For example, the chapter includes sources for bathymetry data, as well as sources for other maritime activities (e.g., locations of protected areas, platforms, etc.) that are useful for monitoring the maritime environment.

The second part of the book focuses on offline maritime data processing techniques. The work described in the chapter of Etienne et al. [7] presents an overview of geospatial relational databases and Geographical Information Systems that can be used in order to store and query data from the maritime domain. This chapter presents practical, hands-on scenarios for geospatial data processing using a modern geospatial relational database management system (PostGIS). The chapter of Tampakis et al. [28] introduces challenges that need to be addressed by existing data management frameworks, focusing on the geospatial and temporal nature of the data (e.g., spatial indices, etc.). This chapter presents techniques for pre-processing, cleaning and knowledge discovery for maritime data. The chapter of Andrienko et al. [3] presents an overview of visualisation techniques of maritime data combined with analytics tasks for data transformation, querying, filtering and data mining.

The third part of the book presents online maritime data processing techniques. The chapter of Patroumpas [21] provides an overview of online mobility tracking techniques against evolving maritime trajectories, focusing on trajectory simplification and compression. The chapter of Santipantakis et al. [26] presents link discovery techniques for maritime monitoring. The aim of link discovery is to enrich the information contained in a single dataset, such as trajectories of vessels, by associating it with other datasets, such as weather conditions. The chapter of Pitsikalis et al. [22] presents methodologies for identifying complex events using AIS data. This chapter first provides definitions of complex events and then describes a formal approach.

The last part of the book describes applications that are based on vessel tracking data. The chapter of Jousselme et al. [16] discusses approaches for performing anomaly detection under uncertainty. Subsequently, the chapter of Ducruet et al. [6] describes graph-theoretical network methods. These methods can be applied to an AIS dataset with port and inter-port data to derive new knowledge about: (i) the relative connectivity of ports, (ii) the impact of cargo diversity on the network structure, and (iii) the impact of structural or geographic patterns on the distribution of maritime flows. Finally, the chapter of Adland [1] describes the use of AIS data for shipping economics.

1.3 VHF Data Exchange System (VDES)

Since the establishment of the AIS protocol for vessel-to-vessel and vessel-to-coast radio communications, AIS became heavily used for safety of navigation and maritime situational awareness. In order to respond to the need of exchanging larger volumes of data through the AIS network which was getting overloaded, the International Telecommunications Union (ITU)[5] decided to revise the VHF marine band by adding designated channels for data transmission. In this direction, the development of the VHF Data Exchange System (VDES) [11] was proposed by ITU. VDES is also expected to increase data security by adding access control and authentication features for AIS radio traffic. This would potentially prevent data jamming, spoofing, etc. The foreseen contributions of VDES to the existing AIS protocol are summarised as follows:

- It supports faster data transfer rates than current VHF data link systems.

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[5] https://www.itu.int/en/about/Pages/default.aspx.

- It supports both addressed (to a specific vessel or a fleet of vessels) and broadcast (to all units in the vicinity) transmissions.
- It offers increased reliability as it is optimised for data communication.
- It addresses the communication requirements for electronic Navigation, also known as eNAV. eNAV aims to improve berth-to-berth navigation and related services through data exchange in higher rates, improving the efficiency of maritime trade and transport. For example, the capability of VDES to transfer increased data volumes will allow the transmission of entire navigation plans, which is not possible currently in AIS. Electronic navigation is described in more detail in Sect. 1.6.1.

1.3.1 VDES Components

VDES is a system that consists of the following three sub-systems:

- AIS, which has been covered earlier.
- The Application Specific Messages system (ASM), which enables the exchange of application-specific messages. Such messages include information like meteorological conditions, collision possibility, danger region alert and route exchange.
- The VHF Data Exchange (VDE) component, that offers increased data transfer rates. VDE has also a satellite component, named VDE-SAT, that enables bidirectional ship-to-satellite communication.

As VDES is not expected to be fully operational until 2023, not all technical specifications about the implementation of VDES are defined at the time of the writing. Therefore, we provide below an overview of the requirements that have been foreseen for the implementation of a VDES network. First of all, as in the case of AIS, antennas will be used for transmitting and receiving data using a terrestrial and satellite link. VDES will build on AIS, so VDES transponders and receivers will be backwards compatible with AIS and ASM (Application Specific Messages system). This means that AIS and AIS-plus[6] equipment (e.g., transponders and receivers) will continue to be operational even after the establishment of VDES, but they will need to get upgraded in order to support the additional functionalities supported by VDES. VDES shore stations will either be upgraded AIS shore stations or new VDES stations at locations where no AIS stations exist.

Apart from the exchange of digital messages, the system should also be able to receive interrogating calls. For example, a vessel should report its position upon request. Other important issues that will be addressed concern the development of data integrity mechanisms and prioritisation of messages to ensure that critical messages (e.g., safety-related) will have higher priority than commercial services.

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[6] AIS-plus is an extension of AIS that includes ASM.

1.3.2 VDES Applications

The new capabilities supported by VDES will be specifically useful for a number of use cases that heavily rely on data exchange between vessels, ship-to-shore and shore-to-ship communication. In this section we provide some examples.

Search and Rescue communications. Search and Rescue (SAR) communications will be improved using VDES and especially its satellite component, VDES-SAT. Since VDES-SAT will be able to receive and broadcast messages even when the coverage is low, it can be used in addition to VDES to relay distress alerts and locating signals.

Vessel traffic services (VTS). The high rate data services offered by VDES could significantly improve the Vessel Traffic Services, facilitating the navigation of vessels in traffic conditions and traffic organisation in general. The vessel traffic image can be created by the fusion of information from different sources, such as radar, AIS and multiple VTS centers (i.e., centers responsible for monitoring and controlling vessel traffic in facilities such as ports), as well as other arbitrary information sent from the vessels (e.g., navigational plan). Reliable and fast data exchange is crucial for VTS in order to provide up-to-date information about the traffic conditions in specific areas and monitor vessel routes and route deviations in an area.

Also, information needs to be exchanged between different parts: (i) vessels, (ii) port agencies, and (iii) VTS centers. In this direction, it might be requested by the VTS that vessels broadcast information regularly, at fixed time intervals, or on demand, i.e., then it is considered necessary. VDES compliant external systems installed ashore and on-board should support the exchange of information in this respect.

Another related service is the Navigational Assistance Service (NAS), which is defined by IMO as "a service to assist on-board navigational decision-making and to monitor its effects". Vessels can request to receive navigational assistance under specific circumstances, such as hardware malfunctions.

Route exchange. One of the most valuable pieces of information that a vessel can provide is its intended route at any given time, together with its current route, so that route deviations can be detected early. Route deviations may occur due to several reasons, such as weather conditions, hazardous situation, equipment failure, etc. In this way, route exchange could assist in the early detection of high risk situations, contributing to maritime safety. At the moment, the crew of a vessel reports changes in destination during a voyage. Using VDES and exploiting the high data exchange rates it offers, entire navigational plans could be transmitted.

Exchanging information about the route of vessels is important also for the shore authorities, in order to assess for example the possibility of congestion in the area of interest. Furthermore, route exchange could enable route and speed optimisation based on external conditions, such as weather and special conditions, hazardous situations, navigational limitations and traffic congestion.

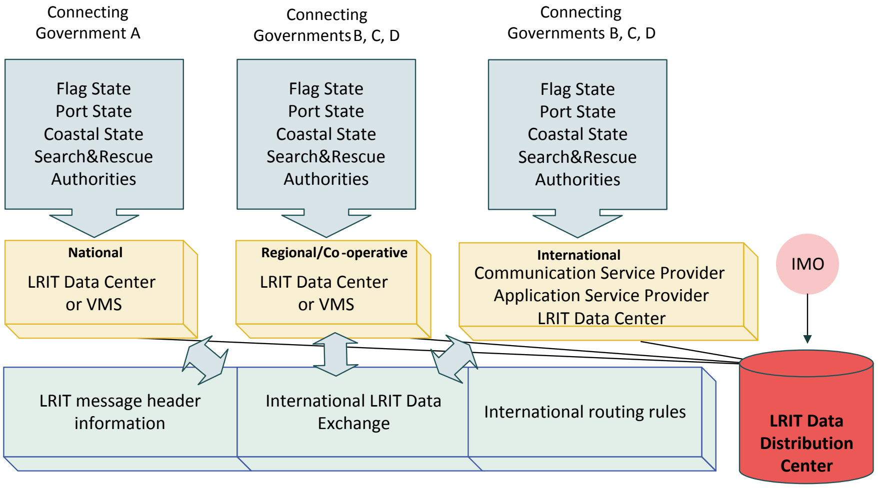

Fig. 1.5 LRIT system architecture (provided by IMO)

1.4 Long-Range Identification and Tracking

The Long-Range Identification and Tracking (LRIT) system is an international system that was adopted by IMO under its SOLAS convention for providing thorough identification and tracking of ships worldwide [14]. Figure 1.5 shows a high-level architecture of the LRIT system. The components of LRIT are described below.

- **LRIT transmission equipment**. This is the equipment that is installed on vessels in order to transmit and receive LRIT messages.
- **Communication service provider.** The communication service provider is responsible for providing the infrastructure and services required to support the communication path between the vessels and the application service providers. The application service providers are described below.
- **Application service providers (ASPs).** The information from the vessels is forwarded to the application service providers by the communication service provider. Once a message is received by the application service provider, it gets enriched with additional information. The complete message is then forwarded to the data centres. The application service provider also provides the implementation of the programming interface to the LRIT equipment that is installed on the vessels.
- **Data centres (DCs)**. Data centres are responsible for receiving, processing, and storing the information transmitted to and from the International LRIT Data Exchange (IDE), which will is described below. Vessels transmit LRIT messages to the data centres that correspond to the administrations that they belong to.
- **LRIT data distribution plan (DDP).** The data distribution plan contains the information regarding the distribution of data to the various Contracting Governments.

This information, accompanied by information about the coastal waters of each Contracting Government, should be available to the Data centres.

- **The International LRIT Data Exchange (IDE)**. The IDE is responsible for routing messages to the appropriate data centres (DCs) based on the address and the URL fields of the message. IDE is not responsible for processing the actual content of the messages. At this stage, only the header content is read.
- **LRIT Data users.** LRIT data users may receive or request LRIT information in their capacity as a flag state, port state, coastal state or SAR service. Flag state is the state under the law of which a vessel is registered/licensed and it is considered as the "nationality" of the vessel. For example, a vessel carrying the Greek flag should operate under the Greek legislation.

1.4.1 Comparison with AIS

AIS and LRIT are independent and complementary. The work described in [5] provides a detailed comparison between AIS and LRIT. AIS messages have higher frequency, as each vessel obliged to have an AIS transponder should send messages every few seconds or minutes, depending on her navigational status and speed (see Tables 1.2, 1.3 and 1.4). On the other hand, LRIT covers areas of 1000 nautical miles off-shore, while terrestrial AIS stations cover approximately 50 nautical miles off-shore. This issue is addressed in AIS with the use of satellites, but communication in LRIT is more secure.

AIS messages transmitted by a vessel can be received by all vessels in the vincinity and ground stations, and are public. A satellite equipped with an AIS receiver collects AIS messages transmitted within the footprint of the satellite. On the other hand, LRIT messages are confidential and are only available to the LRIT data centres. Only contracting governmental organisations have access to this data, as well as Search and Rescue services, so the confidentiality and credibility of the data are ensured. LRIT data are not available for commercial purposes.

Regarding the content of the transmitted messages, AIS messages are richer as they contain more information than the current position at a given timestamp that is transmitted using LRIT. A significant advantage of LRIT, however, is that bi-directional communication is allowed, so for example, a vessel might be asked to report its position at any given time. In that sense, AIS is just a monitoring system, whereas LRIT is a communication system.

1.4.2 LRIT Applications

In [24], a comparison between AIS and LRIT was presented in terms of coverage, confidentiality and accuracy. It is shown how LRIT facilitates the prevention of maritime accidents, as its wide spatial coverage can be exploited to identify potential threats earlier, increasing reaction time and improving maritime safety. In [30], a statistical analysis was presented that showed that the number of piracy attacks declined in the Indian Ocean, an area prone to piracy events, due to the use of vessel tracking systems, including LRIT. Another interesting study that is based on LRIT and AIS data is the estimation of shipping emissions using tracking data, as described in [2]. In this work, the authors correlated vessel tracking information from LRIT and AIS with datasets containing information about the distributions of CO_2 and NO_x emissions from the EMEP[7] and EDGAR databases.[8] This way, density maps were produced showing the distribution of pollutant emissions along shipping lines.

1.5 The Vessel Monitoring System

The Vessel Monitoring System (VMS) is a system for monitoring fisheries [8]. It uses dedicated shipborne equipment that is installed on-board a fishing vessel and it is used to transmit data reports. Such reports contain information about the position of the vessel, speed, course and heading; VMS can also accommodate other auxiliary information (e.g., meteorological conditions). Such reports can either be sent automatically or manually by the operator. Data reports are sent to Fishery Monitoring Centres (FMCs), that store, validate and analyse the data. The transmission of messages from vessels to the FMCs is performed through the deployment of communication systems, both terrestrial and satellite. Some of these systems support bidirectional communication (i.e, not only vessel-to-FMC communication) and this enables the FMCs to poll or query vessels to send information (e.g., position, status of equipment, and so on) on demand.

The main components of VMS are the following:

- The shipborne VMS equipment, also known as the *VMS unit*, is installed permanently on the vessel and it mainly comprises a pair of transmitter and a receiver. The information that is transmitted by a vessel with VMS equipment installed contains the following fields: a unique identifier related to the equipment installed, the vessel's position, the date and time a data report is sent by the transmitter, and the speed, heading, and course of the vessel.
- The Fishery Monitoring centres (FMCs). The FMCs receive the data reports sent from the vessel's VMS equipment, extract the data, perform data validation, store the data and make it available for analysis. The data transmitted to the FMCs from the vessels are private and only accessible by the authorized personnel of the FMC.
- The VMS communication systems. These systems are responsible for securely transmitting data sent from the VMS shipborne equipment to the FMCs. These systems use both space and terrestrial sources. Depending on the communica-

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[7] https://www.ceip.at/webdab_emepdatabase/.

[8] https://www.sec.gov/edgar.shtml.

tion service provider, a VMS communication system might support only one-direction communication (e.g., Argos (CLS)) or multi-directional communication (Inmarsat-C and Inmarsat-D+ or Orbcomm). In one-direction systems, the vessel automatically transmits information at a specified interval. Bi-directional systems allow vessels to be polled or queried by the FMCs. In this way, the FMCs are able to ask for information from vessels on demand.

Notably, VMS is not comparable with AIS, as VMS is an application for monitoring exclusively commercial fishing vessels, while AIS is a communication technology. Data coming from VMS can be used to increase navigational safety, to support Vessel Traffic Services (VTS) and can be further analysed to derive useful information, such as resources optimisation (e.g., fuel consumption). One of the most profound applications based on VMS data is the monitoring of fishing activities, as described in [9]. This work presents a case study that assesses the importance of VMS in fisheries management and focuses on the case of the Portuguese trawl fleet. Another study [25] performs an analysis using VMS data deriving trends in effort and yield of trawl fisheries in the Mediterranean Sea. A similar approach is also used in [31] that describes a method using VMS data to identify and annotate trips made by US fishing vessels in the North Pacific. In the work described in [32] an interesting study using VMS reveals an increase in fishing efficiency following regulatory changes in a demersal longline fishery.

1.6 Advanced Applications and Analytics Based on Maritime Reporting Systems and Data

In this section we describe applications that heavily rely on advanced analytics against data coming from reporting systems. First, we describe electronic navigation, which is an application that attempts to provide assistance to mariners automating navigational tasks as much as possible, in order to minimise human error, and increase safety of navigation. Then, we describe how data coming from reporting systems can be used to increase Maritime Situational Awareness.

1.6.1 Electronic Navigation (eNAV)

We describe E-Navigation (eNAV), which is not a reporting system per se, but an application that requires data fusion from different reporting systems and tools already installed aboard the vessels. eNAV is a broader concept, for which the technical implementations are not yet clearly defined. It is, however, one of the most important use-cases of the systems presented in the previous sections of this chapter, as it can contribute to the safety and security of navigation, automating navigation processing, providing assistance to the vessels crew, thus minimising the possibility of human error in the navigation process.

The definition of eNAV by IMO [15] is provided below.

> **E-Navigation (eNAV)** is the harmonized collection, integration, exchange, presentation and analysis of marine information on-board and ashore by electronic means, to enhance berth to berth navigation and related services for safety and security at sea, and protection of the marine environment.

eNAV systems aim to equip shipboard and ashore users with all the necessary decision support systems that will simplify maritime navigation and communication, making shipping safer and more efficient, providing timely warnings and preventing accidents such as collisions and groundings. It is foreseen though, that electronic navigation systems will not replace the human factor. Mariners will continue to have the same core role in decision making, but eNAV systems will be able to assist them in making more informed decisions. eNAV systems integrate information from various sources such as on-board sensors, hydrographic, meteorological and navigational information sent from ashore or from nearby vessels, alert management systems, etc. The information will be integrated transparently to the user and will be presented through a user-friendly interface. The development of systems that support eNAV should ensure both backward and forward compatibility so that compliance with existing and future systems is ensured, contributing to the interoperability of information exchange between vessels, and between vessels and the shore.

Using eNAV systems, shore-based operators and shipborne users will both benefit from the exchange of navigational information to improve services such as vessel traffic. eNAV systems involve the integration of multiple components that can be categorized as follows:

- *On-board*. Systems that provide assistance to the mariner using an interface, taking into consideration data coming from different sources, such as the vessels' in-house sensors and an alert management system.
- *Ashore*. Shore-based operators could be assisted through the exchange of navigational information to improve services such as management of vessel traffic.
- *Communications*. Navigation-related information could be shared between ships in an area of interest and be made available to third party applications.

eNAV would be particularly useful in the following use cases:

- **Safety of navigation**. The information exchanged through eNAV enables the involved officers (crew members, port authorities) to make decisions based on the navigational status of a specific vessel in relation to external conditions of the area of interest. Navigational information about nearby vessels could be integrated with other sources such as weather data, port congestion information, data describing facilities that could impact the navigational status of the vessel (e.g., wind farms), etc.

- **Environment protection**. Data acquired through eNAV (e.g., route plans), could be fused with other data and further analysed. For instance, a cost estimation analysis could be performed regarding the fuel consumption following different routes, as well as benchmarking of alternative routes with respect to cost and/or time. Different navigational plans could also be compared with respect to their impact on the environment (e.g., “green shipping”).

1.6.2 Maritime Situational Awareness

Maritime Situational Awareness (MSA) is the effective understanding of activities, events and threats in the maritime environment that could impact global safety, security, economic activity or the environment. The primary goals of MSA include “enhancing transparency in the maritime domain to detect, deter and defeat threats” and “enable accurate, dynamic, and confident decisions and responses to the full spectrum of maritime threats”, as stated in the US National Plan for Maritime Domain Awareness [10].

The most widely used collaborative tracking system is the Automatic Identification System (AIS). Collaborative tracking systems rely on the cooperation of the vessel’s crew to provide information regarding the characteristics and the navigational status of the vessel. Therefore, a common criticism regarding AIS-based surveillance is that it says nothing about the presence of non-cooperative vessels, the “non-shiners” or so-called “dark targets”, i.e., the vessels that intentionally do not transmit AIS messages despite being obliged to. Frequently, ships involved in illegal activities, attempt to hide their identification and positional information, either by counterfeiting, masking it or not transmitting at all. Thus, attempting to remain undetected by law-enforcement bodies throughout the whole duration of the illegal activity. On the other hand, non-cooperative systems do not rely on the cooperation with the vessel’s crew to monitor vessels, therefore they are less sensitive to deception, but ship detection, identification and tracking, or speed and heading estimation are more complex, while often limited coverage and their reliability can vary depending heavily on environmental conditions.

The collection, fusion, analysis and dissemination of maritime intelligence and information are the fundamental building blocks of MSA. Data fusion combines multi-origin information to determine relationships among the data; thus improving the understanding of a current complex environment, but also attempting to predict its future state. The advantages in fusing data from multiple sensors and sources are that the final estimated vessel tracks are more accurate and with better confidence, extending to features that are impossible to perceive with individual sensors and sources, in less time, and at a lower cost. Also, it contributes towards better coverage and robustness to failure, thus improving the reliability and quality of the situational picture.

An essential pillar for this is building an accurate model of normalcy. The understanding of the complex maritime environment and a vessel behaviour though, can never be limited to simply adding up and connecting various vessel positions as they travel across the seas. Essentially, vessel-based maritime activity can be described in space and time, while classified to a number of known activities at sea (e.g., fishing). The spatial element describes recognised areas where maritime activity takes place; thus, including ports, fishing grounds, offshore energy infrastructure, dredging areas and others. The transit paths to and from these areas also describe the spatial element, e.g., commercial shipping and ferry routes, etc. While the temporal element often holds additional information for categorising these activities (e.g. fishing period and time of year).

At the core of this process is data mining, an essential step in the process consisting of applying data analysis and discovery algorithms that, under acceptable computational efficiency limitations, produce a particular enumeration of patterns over the data. Hence, extracting patterns also means fitting a model to the data, finding structures, or in general any high-level description of a set of data. Often vessels conducting illegal behaviour and trying to hide their behaviour follow a set of patterns depending on the activity they are engaged in: deviation from standard routes, unexpected AIS activity, unexpected port arrival, vessels in close distance (given a distance threshold), and vessels entering an area they were not expected to. **Anomaly detection**, thus, is considered as the detection of events that deviate from normalcy.

An example of such as deviation is the case of a vessel named Pluto. YM Pluto, departed from Ceuta, Spain on the 25th of April 2013 bound for Rotterdam. On the 27th of April 2013, the vessel was North of the Western coast of Portugal while the weather forecast was Northerly winds of Force 7 to 8 on the Beaufort scale, with severe gusts and very rough seas. During the early morning of 27 April 2013, the master of YM Pluto was on the forecastle deck in adverse weather conditions, attempting to stop a water leakage. Unexpectedly, the ship slammed into a very large wave. The master was exposed to the violent impact of the breaking wave and was severely injured. While arrangements were made to dispatch a helicopter to airlift the master, the vessel altered course heading towards the port of Averio. Figure 1.6 shows the commonly travelled route between Ceuta and Rotterdam in green colour and the actual trajectory of the vessel in red colour. The red star marks the position of the incident. The snapshot is from the Anomaly Detection platform of MarineTraffic,[9] i.e., a prototype system that detects maritime anomalies in real-time (e.g., collisions, vessels in proximity, route deviations, navigation in shallow waters).

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[9] https://www.marinetraffic.com/anomaly-detection (service is accessible for guests after contacting MarineTraffic Research).

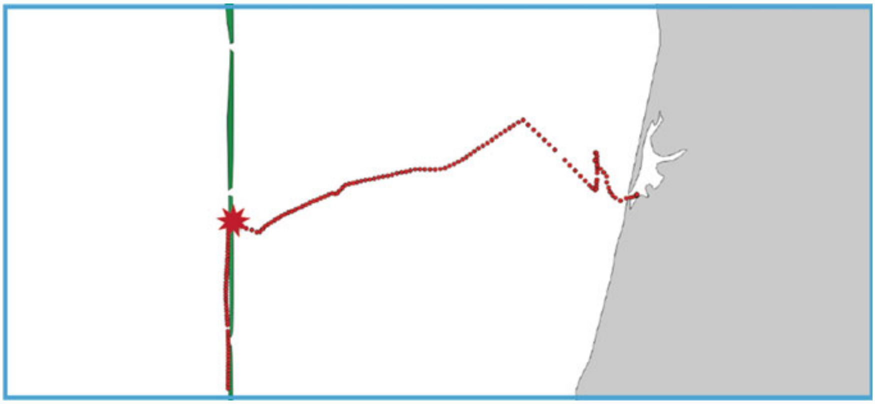

Fig. 1.6 Visualisation of the route deviation of the vessel "YM Pluto" during the time period of the incident while travelling from Ceuta to Rotterdam

1.7 Conclusions

In this chapter we described some of the main cooperative reporting systems that are widely used nowadays, such as the Automatic Identification System (AIS), the Long Range Identification and Tracking System (LRIT) and the Vessel Monitoring System (VMS) for fishing vessels. We also described the VHF Data Exchange System (VDES) that is now being developed and will be completed soon. Its adoption is expected to be highly impactful for maritime safety. Last we presented two applications that rely on data that derive from vessel reporting systems: Maritime Situational Awareness and eNAV.

1.8 Bibliographical Notes

The technical specifications for AIS, VDES, LRIT and VMS can be found in [8, 11, 13, 14]. The eNAV implementation strategy can be found in [12]. Further details about the comparison between Satellite-based AIS and LRIT can be found in [5]. Another comparison between AIS and LRIT is also documented in [24], in which it is showcased how LRIT can contribute to increase safety of navigation.

Watson and Haynie [31] and Watson et al. [32] describe two interesting applications of using VMS data. The former presents and approach that uses VMS to identify shipping routes made by fishing vessels in the US North Pacific. The latter describes how VMS was used in the context of a study that investigates the impact of regulatory changes in the efficiency of fishing activity. Another study described in [9] showcases an analysis based on VMS and AIS data for the Mediterranean Sea to identify trends regarding different types of fishing activities with a focus on trawlers.

Positional data were correlated with data about over-exploitation rates and primary production indices.

In a similar note, the work described in [20] introduces a method that identifies fishing activities of the EU fleet in high spatial and temporal resolution using AIS. Another work described in [18] presents an analysis against AIS data to identify port operational areas. The analysis is based on a distributed implementation of well-known data mining algorithms (e.g., KDE) to improve performance. A similar approach that uses distributed clustering for analysing large volumes of AIS data is described in [27] with the aim of extracting global trade patterns.

Regarding anomaly detection using AIS data, the methodology described in [19] presents an approach for collision avoidance in busy waterways. An anomaly detection framework is also presented in [20] that performs route prediction. An approach for detecting spoofing events against big AIS streams is introduced in [17]. The framework presented in [23] proposes a system based on Run-Time Event Calculus in order to perform recognition of complex events using a set of rules.

Regarding LRIT, the work described in [30] studies the impact of reporting systems on piracy events performing statistical analysis against LRIT data. Alessandrini et al. [2] correlates vessel tracking data with shipping emissions.

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