Marine Policy 93 (2018) 80–92

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Metrics and provider-based results for completeness and temporal resolution of satellite-based AIS services

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ABSTRACT

Collecting AIS messages from ships by satellites allows for maritime situational awareness, and a wide range of commercial applications, at global and regional scales. This work provides methods and indicators for evaluation of the maritime picture in terms of completeness as well as update intervals of ship tracks. The distribution of the maximum daily time gap between messages of each ship gives good understanding of the freshness of the maritime picture. The distribution is however very skewed, and therefore not well described by the mean and standard deviation. As a single indicator, the median value gives a description of the typical quality of service, whereas percentile levels give insight in the spread. The data used were collected in August 2015 in the Eastern and Southern Africa/Indian Ocean region. Four providers of satellite AIS data were used, plus coastal AIS, making the data set one of the most complete available. Typically 575,000 AIS messages from 1630 ships were received per day. The median value of the longest time gap in ship tracks was 4.3 h; and the 70- and 90-percentiles were 6.7 h and 19.5 h, respectively. When subsets of all data are used, starting with the data from one provider and adding the others one by one, it is found that the completeness increases asymptotically, but the median of the maximum daily time gap keeps decreasing linearly, showing that additional data in the first place help to track the ships that are already known.

1. Introduction

The Automatic Identification System (AIS) for ships was introduced by the UN's International Maritime Organisation (IMO) in 2002 as part of the International Convention for the Safety of Life at Sea (SOLAS) [1]. Ships over 300 gross tons on international voyages, cargo vessels over 500 gross tons, and all passenger ships are required to use AIS Class A equipment that broadcasts messages containing their identity, position and other information relevant for the safety of navigation. In addition to the IMO requirements, some jurisdictions require use of AIS on smaller vessels; e.g., all EU fishing ships longer than 15 m must carry AIS [2]. Voluntary use, sometimes using Class A equipment but more often the less expensive Class B equipment, extends the use even further. Some characteristics of AIS, in particular those related to signal reception in satellite orbit, are given in Section 2.

The AIS system was designed for collision avoidance at sea as well as Vessel Traffic Services (VTS) along coasts and in ports. As planned, AIS data soon became used for traffic organisation, navigation assistance and information services through coastal networks. However, maritime situational awareness is also required beyond coastal coverage, and the concept of satellite-based AIS services emerged. Early ideas were discussed in [3,4] and the first feasibility study on satellite-based AIS for wide-area maritime surveillance was presented in 2004 [5]. The satellite AIS services that emerged from 2008 now contribute significantly to search and rescue, fisheries monitoring and control, maritime spatial planning, maritime border security and counter-piracy support, as well as to commercial services for shipping and commodity flow. A recent collection of AIS applications for maritime safety and security can be found e.g. in [6–8].

There are several providers of AIS data, and most of them contributed to the project that was the basis for the studies in this work – see Section 3. (After 2015, new providers have come on the scene.) Even though satellite AIS data are used in a number of applications at regional as well as global scale, the most common specifications for the quality of service as given by providers are the number of messages collected, and the number of ships detected, aggregated globally, per unit time (hour, day or month). Global maps of detected ships and AIS message densities are also shown, e.g. in [9,10]. Such pictures are a combination of the real ship traffic and the detection performance (see Section 2.2) over a chosen time period. A method and results for

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https://doi.org/10.1016/j.marpol.2018.03.028
Received 18 August 2017; Received in revised form 27 March 2018; Accepted 28 March 2018

Table 1
AIS messages used in this work, as well as typical reporting intervals (from [16] Tables 43, 1, 2).

Message ID	Name	Description	Typical reporting intervals vs. speed
1	Position report	Scheduled position report (Class A shipborne mobile equipment)	At anchor: 3 min < 14 knots: 10 s < 23 knots: 6 s
2	Position report	Assigned scheduled position report (Class A shipborne mobile equipment)	As above
3	Position report	Special position report, response to interrogation (Class A shipborne mobile equipment)	As above
18	Standard Class B equipment position report	Standard position report for Class B shipborne mobile equipment to be used instead of Messages 1, 2, 3	< 2 knots: 3 min < 14 knots: 30 s < 23 knots: 15 s
19	Extended Class B equipment position report	Extended position report for Class B shipborne mobile equipment; contains additional static information	As above

tracking capability, defined as the probability of re-detecting ships, was presented in [11], and a modification of the method was used to quantify the detection probability in [12]. Provided that the same time interval is used in the calculations, the detection probability is a good figure for benchmarking systems and services. These results are given with a 2° spatial distribution, and aggregated to regional level. A more sophisticated method to estimate detection probability that optimally exploits the use of more than one sensor has been proposed [13], but in-depth results on satellite AIS have not been published. In any case, the probability of detection quantifies what ratio of ships will be detected; it does not give information about update intervals and its distribution.

Appropriate indicators for the service level [14] and common metrics [15] are still needed. This paper aims to contribute to that discussion. Section 4 presents the proposed methods for calculation of the performance metrics and Section 5 presents results from the Indian Ocean region.

Before going into detail about the analysis, a look at the various uses of AIS data and an indication of the required quality of service is appropriate:

- For ship traffic patterns and marine spatial planning, it is often acceptable to observe a representative fraction of the ships at a representative, but not necessarily high, temporal resolution, without any real-time requirement.
- To assist ships in distress at sea, in search and rescue operations, as well as in order to send alerts to ships about safety or security threats, a complete and timely picture with accurate positions is essential.

In addition, for users in maritime surveillance and coordination centres, it is important to know whether the absence of updates of a specific ship is within the natural variation, or an anomaly worth investigating.

For any satellite AIS provider, or set of providers, the quality of service is dependent on the ship detection probability (in turn dependent on geographic area and the performance of the AIS receiver) and the satellites' coverage area (each satellite's orbit and the constellation). The following topics are studied:

1. How complete is the maritime picture, i.e., what fraction of the AIS-carrying ships is observed?
2. What is the temporal resolution of the ships tracks, i.e., what is the update interval of the positions?
3. What indicators are appropriate to characterise the temporal resolution, i.e., how can the typical update interval and the variation best be presented?

With respect to points 1. and 2., the relevant required completeness and update interval depend on the application. The reader can compare the results vs. number of providers in Section 5.4 to their own requirements, keeping in mind that the results are from the equatorial region in a relatively benign signal environment. The aspect of timeliness/latency is not studied here.

Concerning point 3., as well as the variation of 1. and 2. with the number of satellite AIS data providers, this paper provides methods for analysis of the quality of the maritime picture (from any number of providers), as well as for studies of its variation with the number of providers used.

A discussion of the suggested metrics and the results is given in Section 6, and the conclusions are found in Section 7.

2. Some characteristics of AIS systems

2.1. The AIS standard

The AIS standard has 27 message types, with different content and functions [16]. In every AIS message the ship is identified with the 9-digit Maritime Mobile Service Identity (MMSI) number that is unique for the AIS transponder on the ship.

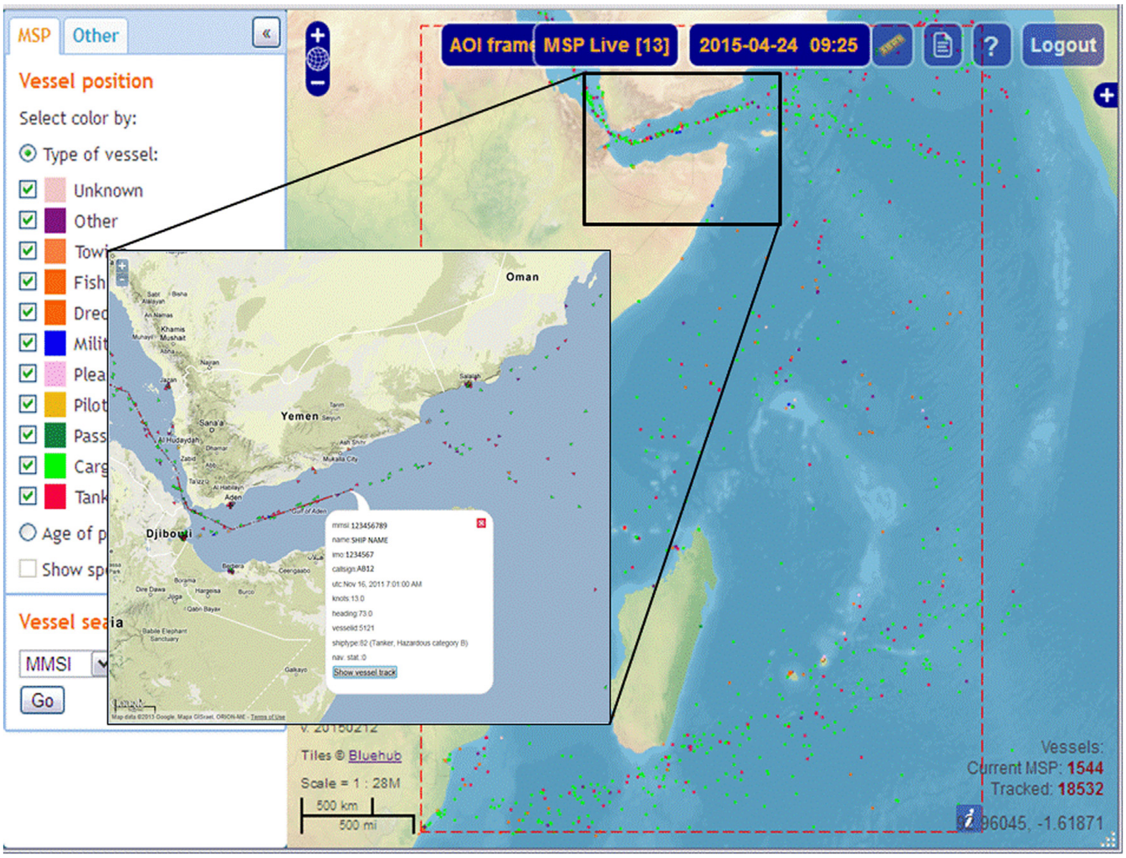
In this study, the dynamic messages (that provide ship position data) have been analysed, see Table 1. The first generation of AIS satellites receive the messages intended for ship-to-ship and ship-to-shore exchange of data using self-organized time division multiple access (SOTDMA). In version 4 of the standard, message 27 *Position report for long-range applications* was introduced. More recent satellite AIS receivers receive this message, but it was not available in the data analysed here.

The output power is 12.5 W for Class A and 2 W for Class B equipment. The lower transmission power and longer reporting interval gives a lower detection probability for vessels using Class B equipment than for vessels using Class A.

The SOLAS requirement [1] states that AIS equipment shall be operational as long as international agreements, regulations or standards do not require protection of the navigation information, and IMO resolution A.917(22) allows the ship masters to switch off the AIS in specific areas where threat of attack by pirates or terrorists is imminent.

2.2. Satellite AIS

The AIS standard ensures exclusive (i.e., non-overlapping) use of the time slots within the SOTDMA organisation geographical area that has a radius up to 50 nautical miles (actual range can vary depending on propagation conditions), matched to the range of terrestrial receivers. Satellites, however, receive transmissions from a much wider area; hence messages may overlap in time, especially in areas with a lot of ship traffic. This is known as message collision, and it makes the decoding challenging. Even though the signal strength in satellite orbit is significantly lower than on the ground, the signal level is less of a



mmsi:123456789
name:SHIP NAME
imo:1234567
callsign:AB12
utc:Nov 16, 2011 7:01:00 AM
knots:13.0
heading:73.0
vesselid:5121
shiptype:82 (Tanker, Hazardous category B)
nav. stat.:0

Fig. 1. Maritime situational picture in the Western Indian Ocean produced by PMAR-MASE. Ships are colour-coded according to type. Map background from Natural Earth [24].

problem than the messages collisions. In addition, terrestrial interference from land-based systems re-using the maritime frequencies occurs, especially in Europe, Central- and North America, and parts of Asia. As a result of message collisions, signal level and terrestrial interference, satellite AIS only receives a fraction of the broadcasted messages in its coverage area successfully.

Considering a typical satellite at 600 km altitude, the visible ground area has a width of 5300 km. Ships in the middle of the track are in the field of view for 15 min, but the time decreases towards the edges. The ship antennas are omnidirectional, having a “donut shaped” beam, transmitting most of the power towards the horizon and little upwards. The receiving antennas on the satellites are typically also omnidirectional, and during the overpasses the high-sensitivity part of the receiving antennas will cover any area below the satellite. The signal strength is also dependent on the distance between the ship and the satellite, so although the distance to the nadir targets is smallest, those toward the horizon may be easier to detect because of the antenna beams. A high concentration of ship traffic or a terrestrial interference source anywhere within the visible ground area will contribute to message collisions. This can be alleviated by the use of a directional receiving antenna, but that is not usually applied.

Overpasses are separated by the satellite revolution period that results in gaps of around 90 min between consecutive overpasses. With respect to revisit rate, different orbits have different properties. Most of the AIS satellites are in sun-synchronous polar orbits, because they have been launched as auxiliary payloads, at reduced cost, together with earth observation satellites. A property of the sun-synchronous orbits is that the satellites pass over at the same local time every day. Due to the rotation of the Earth a point near the equator will rotate out of the swath of an AIS satellite in sun-synchronous orbit after four overpasses, and be re-acquired half a day later. This results in gaps of the order of 9 h at equatorial latitudes. As the circumference of the parallels gets smaller at higher latitude the number of overpasses increases to 15 per day at the poles.

A few AIS satellites are in equatorial orbit, meaning that they cover an area near the equator at any time with a revisit time of approximately 90 min; hence the time of the overpass varies from day to day, and areas high north and south are not covered at all. Some satellites have orbits in between polar and equatorial, called inclined orbits; also these have overpasses that vary from day to day.

The numbers above apply to a single satellite. Using several satellites, the number of passes increases and the time gaps are shortened. However, given the limited probability of detection of an AIS message and the finite duration of a satellite overpass, it cannot be expected that all ships within the coverage area will be detected in each satellite pass, see e.g. [11] for first access as well as accumulated figures for 24 h, and [12] for a period of 36 h. Despite improvements in satellite technology as well as increasing number of satellites, most satellite AIS services are still based on discrete snap shots in time rather than the continuous coverage obtained within the range of coastal networks.

Considering all the above, the satellite AIS performance is dependent on a series of factors:

- Regarding the satellite:
  - Orbit type (sun-synchronous/inclined/equatorial/elliptic);
  - Orbit altitude;
- Regarding the sensor and processing:
  - Sensitivity of the receiver;
  - Antenna beam;

  - ○ Sophistication of the algorithms for message decoding;
- Regarding the geographic area:
  - ○ Ship traffic density;
  - ○ Radio interference from other sources.

3. AIS data used to build the PMAR maritime picture

The AIS data analysed in this work were collected in the third Piracy, Maritime Awareness and Risks (PMAR) campaign, a capacity building effort carried out by the Joint Research Centre of the European Commission (JRC) under the Programme to Promote Regional Maritime Security in Eastern and Southern Africa and Western Indian Ocean region (MASE) [17–19]. Building on experience from two earlier PMAR-trials [20–23], PMAR-MASE made the transition to operational services, providing a maritime situational picture over the Western Indian Ocean to the Anti-Piracy Unit of the Indian Ocean Commission (IOC) in the Seychelles, and the Regional Maritime Rescue Coordination Centre (RMRCC) run by the Kenya Maritime Authority in Mombasa, Kenya, from September 2014 to September 2015. Fig. 1 shows an example of the maritime situational picture: The dashed red box (longitude 31–68°E, latitude 30°S to 19°N) is the area of interest, which has a total sea surface of 4.28 million square nautical miles; the black box is a zoom on the Gulf of Aden, including a ship track and information about the ship.

Satellite AIS data were obtained from four providers, in addition to coastal AIS data, as listed in Table 2. The number of satellites offered by each provider varied over the year, the numbers and names in the table refer to the period 24–30 Aug 2015 that is used in this work. Some satellites are distributed by multiple providers; in this analysis each satellite is only taken into account once, under its original provider. ORBCOMM Generation 2 (OG2) was in 2015 a constellation of 6 satellites whose data were distributed to European customers by LuxSpace, together with their VesselSat-1 and -2 data. The coastal Maritime Safety and Security Information System (MSSIS) network of the U.S. Navy/U.S. Department of Transport covers some major ports and limited areas near the coast.

Regarding the factors that influence the performance, listed at the end of Section 2.2, 10 of the satellites are in polar orbit, passing at a fixed local time each day. Two inclined orbits are used, one with the six OG2 satellites and another with NORAIS-2 on the International Space Station (ISS), leading to daily shifting overpass times. Orbit altitudes vary between 405 km for NORAIS-2 on the ISS, resulting in a footprint of 4400 km diameter, and 820 km for Resourcesat-2, resulting in a footprint of 6100 km; the latter is therefore more prone to message collisions. Figures on the individual receiver sensitivities are not available. All systems use omnidirectional antennas, the receivers have different levels of sophistication in the message decoding. Regarding the geographic area, the oceans in general are not extremely busy, but in some areas around Europe, America and China message collisions are known to cause problems.

Table 2
Providers used and their satellites for the week 24–30 Aug 2015. Orbit and altitude data are from [26]; altitude is the average of perigee and apogee, and may change over time.

Provider	# Satellites	Satellite names	Orbit	Altitude
Norwegian Coastal Administration/FFI	3	AISSat-1, -2 NORAIS-2	polar 52°	630 km 405 km
exactEarth	4	ExactView-1 (rEV-01) ExactView-6 (rEV-02) Resourcesat-2 (rEV-05) Aprizesat-7 (rEV-06)	polar polar polar polar	817 km 660 km 820 km 650 km
SpaceQuest	3	Aprizesat-8, -9, -10	polar	670 km
ORBCOMM/LuxSpace	7	VesselSat-2 OG2 (6 satellites)	polar 47°	485 km 700 km
Maritime Safety and Security Information System (MSSIS)	–	(coastal AIS)	–	–

Table 3
The five subsets of data used.

provset	Number of data providers	Number of additional data sources	Total number of data sources
1	1	3 satellites	3 satellites
2	2	4 satellites	7 satellites
3	3	3 satellites	10 satellites
4	4	7 satellites	17 satellites
5	5	Coastal	17 satellites + coastal

4. Methodology

4.1. General approach

Table 3 shows the categorical variable *provset* introduced to denote the subset of providers whose data are used to construct the maritime picture.

To present the quality of service for a *provset*, quality indicators are first defined per ship per calendar day. Secondly, the quality of the entire maritime picture is characterised based on the statistics over the collection of all ships in the maritime picture. Finally, the completeness as well as the temporal characteristics are studied comparing results after averaging over a number of days. The notation and content of these three levels of indicators are presented in Table 4, the complete definition is given in Section 4.2.

4.2. Definition of performance indicators

The indicator values estimated for each ship make up a sample of the form S(*ship, day, provset*) that characterises how well the ship can be detected and tracked. The statistics of the form D(*day, provset*) of these values are computed over all ships to characterise the daily maritime picture. The performance indicators of the form P(*provset*) are averages of the daily indicators, used to characterise the quality of service aggregated over the time.

4.2.1. S(ship, day, provset)

The basis for the performance analysis is the messages from each ship and the time between messages. For ship tracking, regular position updates are more valuable than concentrated bursts of messages during a satellite pass. Therefore, the concept of an ‘observation’ is defined as an essential update of the ship position, as explained in the second bullet point below. The limits of 1 h and 3 h for ‘fresh’ data are in line with the requirements published by the European Space Agency (ESA) [25], worked out in cooperation with authorities responsible for EU policy on maritime affairs and fisheries.

The six indicators of the form S(*ship, day, provset*) are:

- Number of messages (*n_mes*): the count of messages.
- Number of observations (*n_obs*):
  - ○ for satellite AIS data an observation is attributed to the first message in each satellite pass;
  - ○ for coastal MSSIS data an observation is attributed to a message

Table 4
The three levels of metrics with indicators used to characterise the quality of service.

Notation	Description of selected indicators	Applies to
S(*ship, day, provset*)	• The number of messages received per ship; • The longest time gap between messages.	Individual ships, on a certain day, for a certain subset of providers.
D(*day, provset*)	• The total number of ships detected; • The total number of observations; • The mean number of messages per ship per day; • The median value of longest time gap between messages per ship per day.	All ships, i.e. the entire maritime picture, on a certain day, for a certain subset of providers.
P(*provset*)	• The weekly mean of the total number of ships per day; • The weekly mean of the daily mean number of messages; • The weekly mean of the median value of longest time gap between messages per ship per day.	The entire maritime picture, for a certain subset of providers, for the area and time period used.

received one hour after the previous observation.

- Number of hours with messages (*n_hrs_w_mes*): the number of clock hours in the day in which one or more messages are received (an integer between 1 and 24).
- Longest time gap (*dT_max*): the longest time gap between messages.
- Total time of data older than 1 h (*dT* > *1h_accu*): the accumulated time over the day the most recent message of a ship is older than 1 h; the indicator measures the absence of 'fresh' data. The 1st hour of the day is considered following the 24th hour, which may give a contribution if the time between the last and first message is more than 1 h.
- Total time of data older than 3 h (*dT* > *3h_accu*): similar to the indicator above, but accumulates the time the most recent message is more than 3 h old.

An example for one ship is given in Section 5.1 (Fig. 2), and the use of the indicators to illustrate the quality of the maritime picture in maps and histogram distributions is shown in Section 5.2.

4.2.2. D(day, provset)

To find the most appropriate metrics to characterise the quality of service on a daily basis, D(*day, provset*), the statistical characteristics of S(*ship, day, provset*) are studied. The 28 indicators are:

- number of messages received, n_MEST (the sum of the n_mes over all ships),
- number of ships observed, n_MMSI (the count of MMSI's).

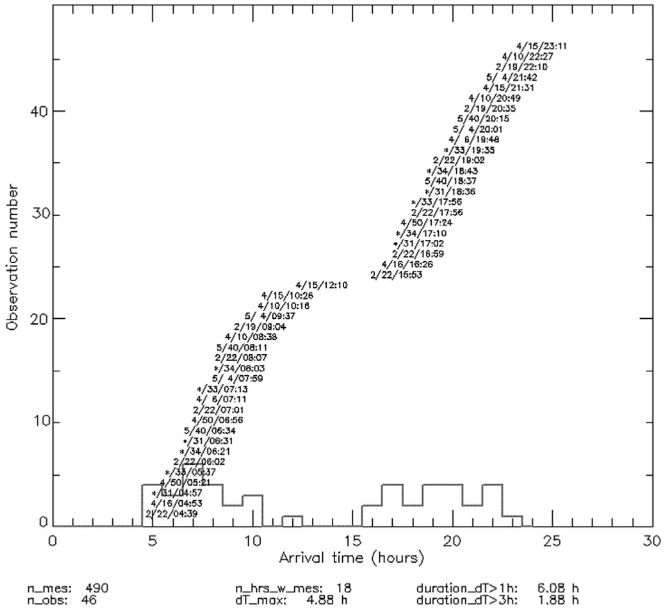


Fig. 2. Histogram plot of number of observations per hour for one ship on 27 August 2015. The annotation shows the provider/platform/hh:mm (UTC) of the first message in each pass.

as well as statistical values for each of the six indicators in S(*ship*, *day*, *provset*)

- mean,
- standard deviation,
- median,
- maximum or minimum.

and additionally for the distribution of dT_max, the

- 70-percentile, and the
- 90-percentile.

An example is given in Section 5.2 (Figs. 3 and 4), the daily results for the period is shown in Section 5.3 (Fig. 5) and discussed further in Section 6.

4.2.3. P(provset)

To describe the maritime picture in a longer time period as well as the variation with number of providers, the P(*provset*) contain the

- mean, and the
- median.

values of the D(*day, provset*) indicators. Results are presented for one week for all four satellite providers, P(*provset* = 4), in Section 5.3 (Fig. 5); the variation of P(*provset*), where *provset* = 1–5, is studied in Section 5.4 (Fig. 6).

5. Results

5.1. Observations of one ship during one day

The observations of one ship on 27 August 2015 are shown in Fig. 2. The histogram plot shows the number of observations per hour, in bins of +/− 0.5 h around each whole hour. The annotations show what provider and platform (satellite) made the observation at what time. The ship was in the central part of the area of interest, outside range of the coastal stations. It was therefore not detected by MSSIS, but by all satellite AIS providers. The ship was not observed until 04:39; in the 5th hour-bin four observations were made. The number of observations per hour peaked to six in the 7th hour, whereas zero observations were made for three consecutive hours after the 12th hour.

The groups and gaps of observations show that many satellites pass over between approximately 5 and 10 UTC and also between 17 and 22 UTC. The ship's sample values are shown below the plot; *n_mes* = 490 messages are received, giving *n_obs* = 46 observations. The *n_hrs_w_mes* = 18 are the actual hours of the day; the reason the number

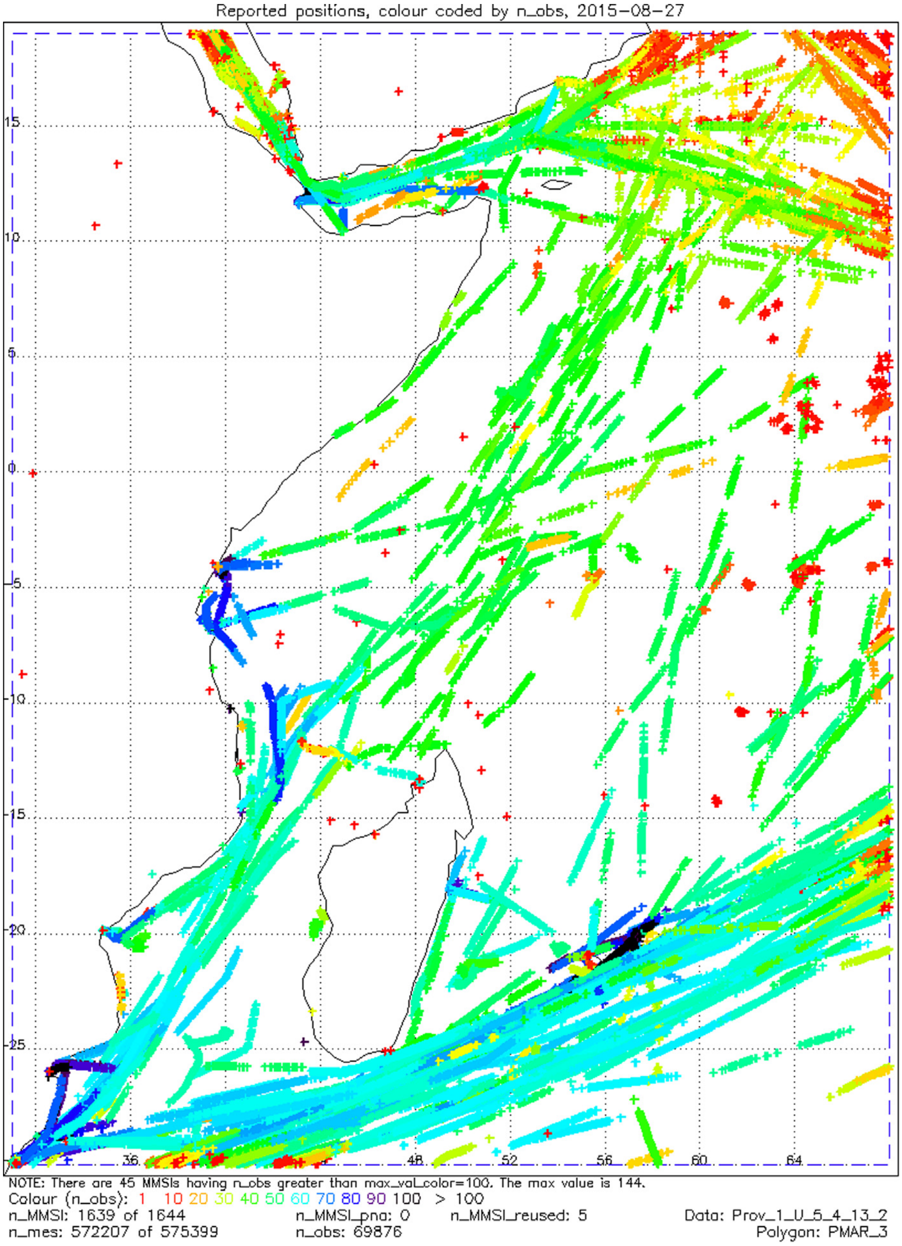


Fig. 3. All ship positions received on 27 August 2015 plotted using a colour scale representing the number of observations for each of the 1639 ships.

is higher than the number of bins with observations is that the *hh*-part of timestamp is used and all messages are considered, not only the first that is used as the time stamp of the observation. The longest time gap between messages is $dT\_max = 4.88$ h. The total time the data of the ship are 'un-fresh' relative to update intervals of 1- and 3 h is 6.08 h and 1.88 h, respectively.

5.2. Observations of all ships during one day

The map in Fig. 3 shows all the ship positions received on 27 August 2015 coloured by the number of observations per ship for $provset = 5$. The total number of MMSI's observed is 1644, of which five had a duplicate MMSI number (see Section 6.1), and hence are not used in the analysis of the quality of service. The total number of messages from the 1639 ships with valid tracks was 572,207, resulting in 69,876 observations.

From the colours it can be seen that the detection probability is a little better in the southern than the northern area. Along the perimeter lower values (red; < 10 observations) occur because ships enter or exit the area during the day, and within range of the few coastal AIS stations the values can get high (dark blue and black; > 100 observations). A few of the red symbols with $n\_obs = 1$ are scattered randomly over the area, including on land. Such detections may be false alarms, e.g. from decoding errors, but some are actual ships that are difficult to detect.

The histograms in Fig. 4 show the distribution of the respective indicator values for all ships; the number of occurrences sums up to 1639 for each histogram. The mean and median values are shown on the right side of each plot. From the top, the distributions show the following characteristics for the performance indicators:

- Number of messages (*n_mes*): The distribution has a peak of 112 ships in the first bin (1–4 messages), reflecting the false alarms (due to MMSI errors), the perimeter effects and the ships that are difficult to detect, but is in general rather flat and broad. The tail (*n_mes* > 500) extends beyond what is plotted.
- Number of observations (*n_obs*): The distribution has a peak of 83

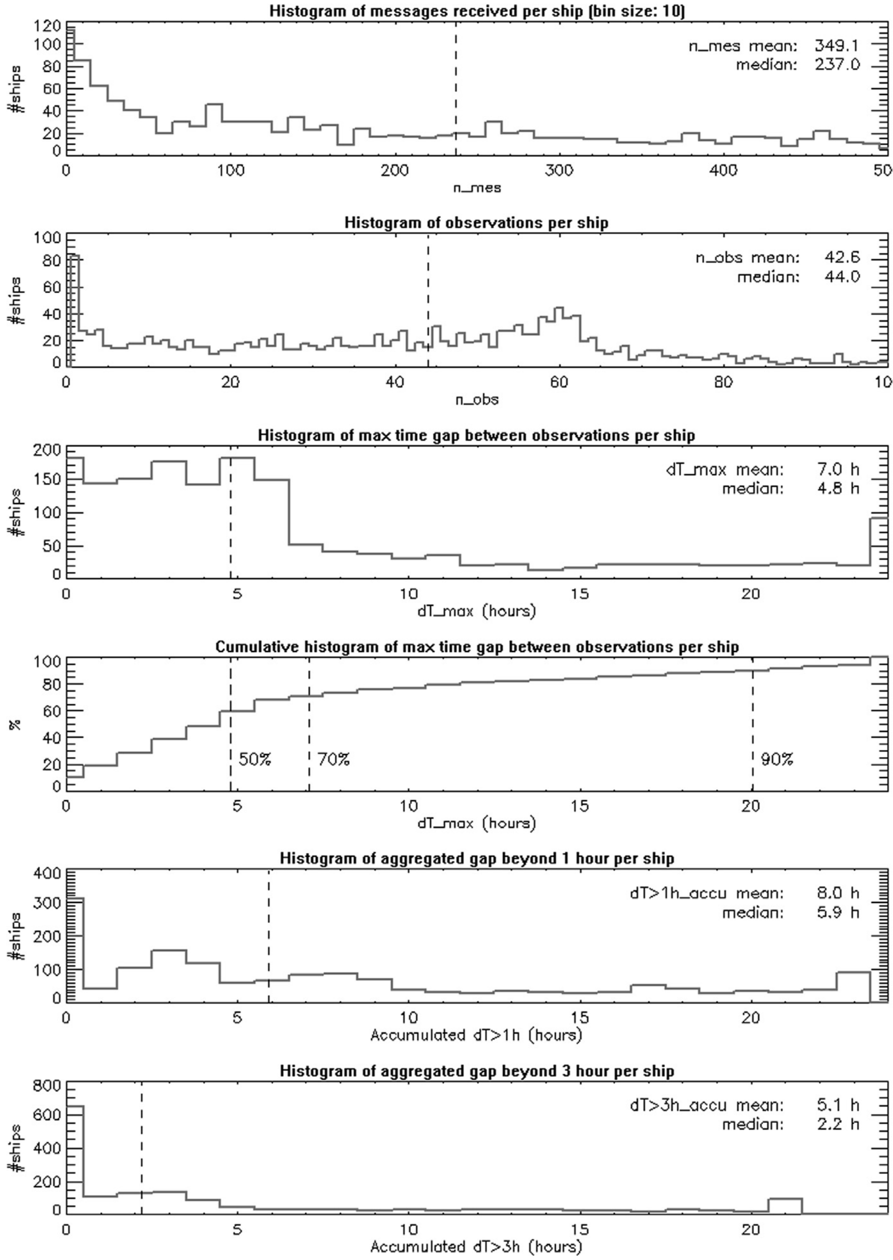


Fig. 4. Histograms of indicators for 1 639 ships from D(*day* = 27Aug2015, *provset* = 5). In the top two graphs, the tail (*n_mes* > *500*, *n_obs* > *100*) extends beyond what is plotted.

ships with one observation (those that have low *n_mes*), but differs from the *n_mes*-distribution in that also 44 ships have 60 observations; the median value is 44 observations.

- Longest time gap (*dT_max*): The median is 4.8 h, which is 2.2 h less than the mean that is 7.0 h. Most ships have values below 6.5 h, whereas the 83 ships with one observation are found at 24 h.
- Cumulative distribution for longest time gap (*dT_max*): the curve rises linearly up to 5 h, then somewhat slower up to 7 h where 70% is reached, and then slowly up to 20 h where 90% is reached and eventually to 100% at 24 h.
- Data older than 1 h (*dT* > *1h_accu*): There are 312 ships in the 0th-bin, 19% of the total, that meet a requirement for update every hour. The median is 5.9 h, which is 2.1 h less than the mean value of 8.0 h.
- Data older than 3 h (*dT* > *3h_accu*): There are 647 ships in the 0th bin, 39% of the total, meeting the requirement for update every 3rd hour. The median is 2.2 h, which is 2.9 h less than the mean value of 5.1 h.

The ship used as an example in Fig. 2 is in the central part of these distributions, and can be referred to as a typical ship. The broadness of *n_mes* gives a first indication of the variation in the capability to track the ships: ships with 500 messages per day will be easy to track, ships with 1 message per day cannot be tracked, and everything in between. Considering the cumulative distribution of *dT_max*, using the 10- and 90-percentiles as limits, it can also be stated that gaps between 0.5 h and 20 h should be considered normal. This range is wide; at the low end ships can be tracked very well, at the high end hardly at all.

The distributions are not bell shaped (in statistics called normal distribution), but instead skewed, asymmetric and sometimes with a long tail. The central tendency and the typical spread is therefore not well described by the mean and standard deviation, which for a normal distribution are measures of the centre and the range within which you find most of the occurrences (actually 34% within one standard

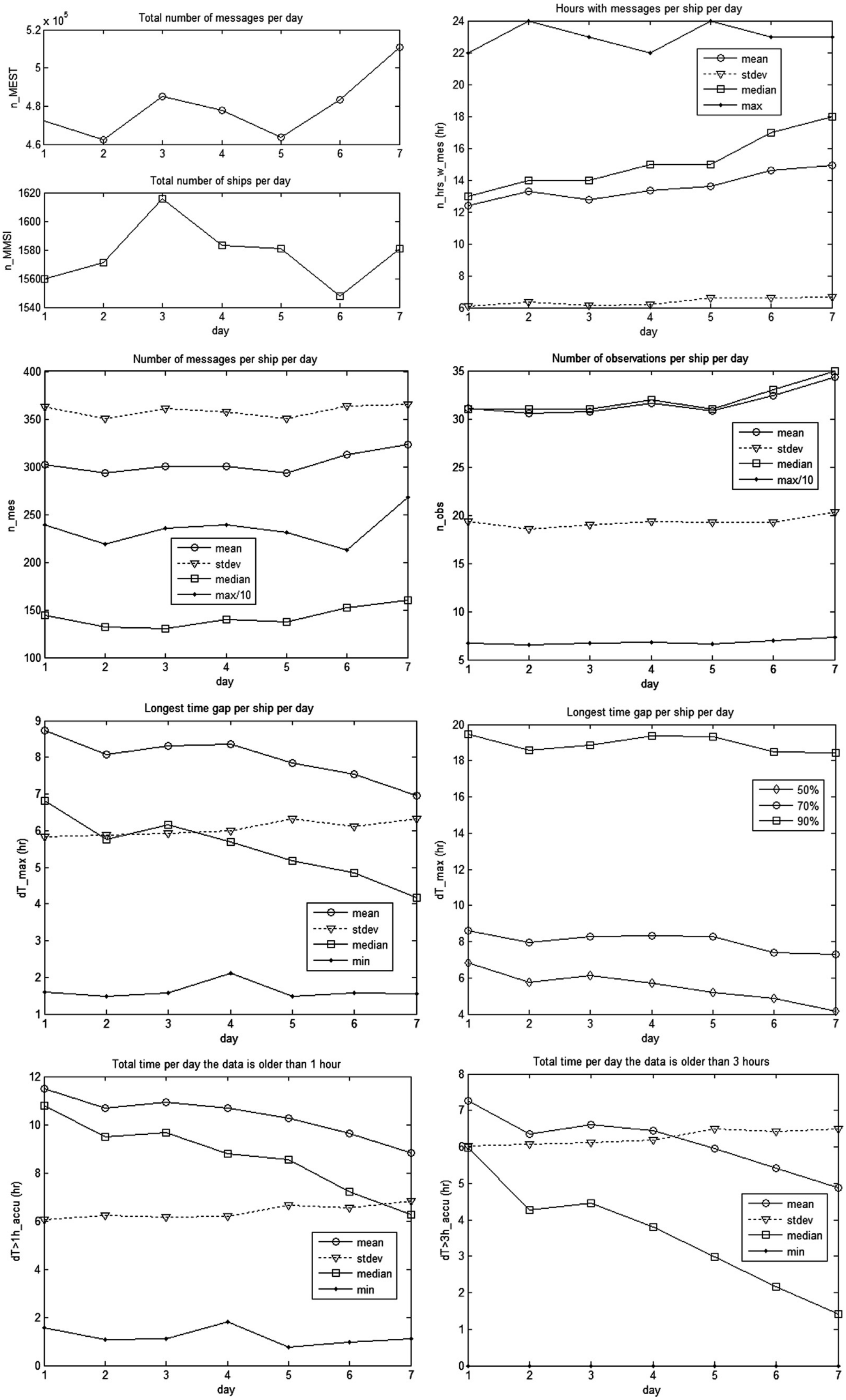


Fig. 5. Plots of daily indicators for seven days; D(*day*, *provset* = 4), where 24–30 August 2015 is plotted as *day* 1–7. All statistics (sum, mean, median, standard deviation, min, max) are calculated over all ships, for each *day* and *provset*. Note that for 'Longest time gap per ship per day' the median curve in the left plot is the same as the 50% curve in the right.

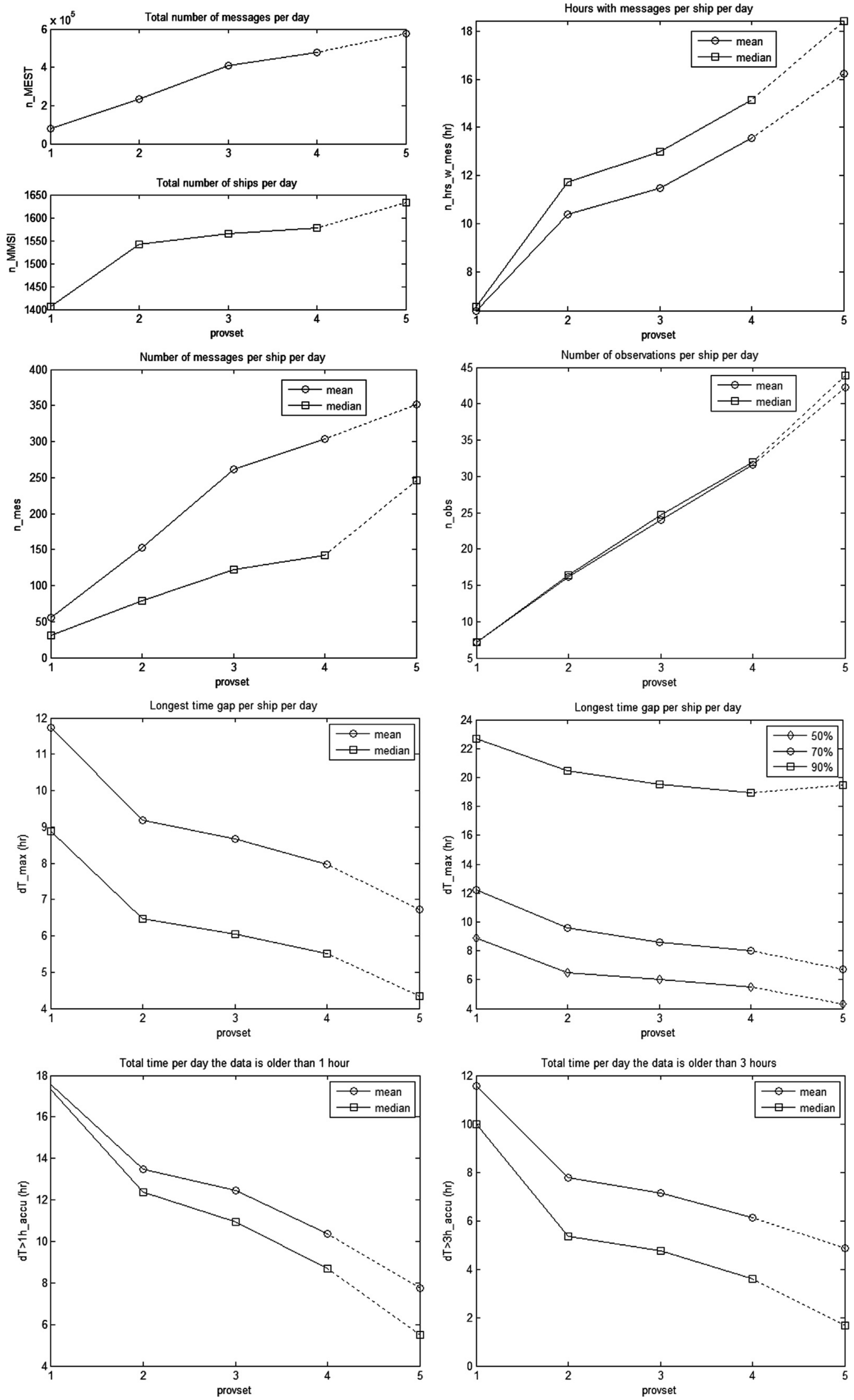


Fig. 6. Plots of averaged mean (labelled ‘mean’) and median values (labelled ‘median’) of the daily indicators; P(*provset*), where *provset* 1–4 are connected by solid lines, and the connection to the results including coastal AIS data (*provset* 5) is made with dashed lines. The values of Table 5 are included in these plots.

deviation to each side of the centre for a normal distribution). Another commonly used measure of the central tendency is the median value: The middle score for a set of data that has been arranged in order of magnitude; also called the 50-percentile. When the distribution is skewed the standard deviation is not well suited to describe the spread of the distribution. To present the typical deviation (after this referred to as the spread) other characteristics of the distribution like quartiles and percentiles, for example the 10- and 90-percentiles, can be used. The distribution of the longest time gap, *dT_max* in Fig. 4, illustrates how different the mean and median values describe the distribution over all ships; whereas the median is always in the centre, the mean is here close to the 70-percentile. The seven-day statistics in Fig. 5 shows that the standard deviation *dT_max* exceeds the central tendency given by the median five of the days

The main cause of temporal gaps is the lack of satellites passing over during parts of the day. Gaps in the hours with many satellites passing are due to the limited detection probability, and ships transmitting few messages or with low power are difficult to detect. This includes ships using Class B equipment, as well as ships with Class A equipment at anchor (reporting only every 3 min). Finally, part of the apparent temporal gaps is due to ships entering or leaving the area.

5.3. Daily performance variations with all satellite providers

The quality of service and its variation over a week is examined in this section using all satellite data, D(*day*, *provset* = 4) where *day* is 24, 25, …,30 August 2015. The values of the indicators are plotted in the various panels of Fig. 5 as a function of the day of the week. Note that the values for *day* 4, which is 27 August 2015, do not equal those mentioned in Fig. 4 because the latter includes MSSIS data.

Table 5 lists the statistics averaged over all seven days; the column for *provset* 4 corresponds to the data plotted in Fig. 5, the column for *provset* 5 includes MSSIS data that were not included in the plots, giving the possibility to compare the metrics for the area when the coastal data are included. Note that the improvements in the coastal areas are actually bigger than shown, but the improvements do not apply at all to the oceans. In the lower part the time-averaged values of the daily statistics are shown; the first columns show the mean over all days of the *daily median* values, the last column the mean over of the *daily mean* values, so that the difference of the median and mean as daily indicators can be seen.

5.4. Incremental value of additional providers

To quantify the value added by a new provider in terms of completeness in number of ships and temporal resolution of the tracks, the P (*provset*) indicators averaged over the seven days are studied. Fig. 6 shows plots of the indicators as a function of the number of satellite AIS providers (*provset* 1–4) and finally also with coastal AIS (*provset* 5), see Table 3. The indicators that are plotted are the averaged mean and median values over all ships. For *dT_max* also the 50%, 70% and 90% values are plotted (the standard deviation and minimum or maximum values from Fig. 5 are not included).

6. Discussion

6.1. Accuracy and error sources

The metrics for the detection and tracking of each ship are based on the MMSI number as unique identifier. However, even though the MMSI number is supposed to be unique, some numbers are used by more than one ship. For ship tracking it is often possible to recognise such cases, among others by the occurrence of jumps in the ship's position corresponding to unrealistically high speeds. This check was done, and data from those MMSI numbers were not used in the calculation of the performance indicators because they would unjustly bias the indicators. The fraction of the excluded MMSI numbers is relatively low, less than 0.5%. This means that the number of detected AIS-carrying ships may be 0.5% higher than the number of unique MMSI numbers observed.

On the other hand, some of the received AIS messages are erroneously transmitted or decoded, and may result in MMSI's with a single message. Such single-message MMSI's give rise to an overestimation of the number of detected ships. The magnitude is more difficult to estimate, but one indication can be the fraction of MMSI numbers for which only a single message is received during a multi-day period. This fraction is of the order of 4%, but many of these may be nonetheless real ships.

Taking the above into account, the number of unique MMSI numbers is equated with the number of detected AIS ships, with an error of the order of 1%.

For the temporal indicators, the occurrence of a single message with erroneous MMSI will contribute negatively to the performance, with a corresponding time gap of 24 h. Along the perimeter, there are ships that enter or leave the area that will have a similar impact on the results.

Table 5

Performance indicator values P(*provset*) obtained over the 7-days analysis period. The statistics (mean, standard deviation) are calculated over the days.

provset Indicator	4 (17 Sat)	5 (17 Sat + MSSIS)
Mean and standard deviation over all days	of daily total	of daily total
Mean *n_MEST*	478,053	573,551
StDev *n_MEST*	15,881	15,601
Mean *n_MMSI*	1574	1630
StDev *n_MMSI*	20	17

provset Indicator	4 (17 Sat)	5 (17 Sat + MSSIS)	5 (17 Sat + MSSIS)
Mean value over all days	of daily median values	of daily median values	of daily mean values
n_mes	142.1	246.3	352.0
n_obs	32.0	43.9	42.3
dT_max (h)	5.5	4.3	6.7
n_hrs_w_mes	15.1	18.4	16.2
dT > 1h_accu (h)	8.7	5.5	7.7
dT > 3h_accu (h)	3.6	1.7	4.9

It should be noted that this analysis is made using messages from AIS Class A and B equipment combined, which gives a higher number of ships in the picture but a lower temporal performance.

6.2. Daily variations

The $D(day, provset = 4)$ indicators, plotted in Fig. 5, and the resulting $P(provset = 4)$ metrics make the basis for the discussion of the performance indicators and the characterisation of daily variations in the 7-days period. From the mean and standard deviation of the number of messages and observations in Table 5**,** the long-term variation in the total number of messages is 3%, and in the number of ships only 1%. The variations are due to the number of ships actually present in the area each day, the fraction of broadcasted messages successfully received, and how the satellite overpasses fit into the calendar day.

The statistics of the six indicators calculated per ship are first discussed with respect to the indicators as such, using the daily values plotted in Fig. 5 and their weekly means. For the daily number of observations per ship (n_obs), the mean and median curves almost overlap, having values near 32, and the standard deviation, on average 19.3 for the 7-days period, gives a good measure of the spread of the distribution. Also for the number of clock hours a ship is detected ($n\_hrs\_w\_mes$) the difference is small: The weekly mean of the medians is 15.1 h, and of the means it is 13.6 h, hence the distribution is a little skewed, but the standard deviation still gives a good description of the spread with values around 6.4 h.

For the number of messages per ship (n_mes) the weekly mean of the medians is 142.1, of the means 303.7, and of the standard deviations it is as high as 358.6. The difference between the two indicators for the central tendency is large, and the large standard deviation reflects the asymmetry and extended tail of the distribution (ref. Fig. 4 top panel).

Temporal indicators have a significant difference between the two values for the central tendency. The median is always lower than the mean, indicating that the distribution is skewed by some high values (long time gaps). The standard deviation is of a similar value as the central tendency, and even increasing towards the end of the period when the time gaps as such are reduced; the curves for the longest time gap (dT_max) illustrate this. With the standard deviation unfit to characterise the spread of the distribution, the 70- and 90-percentiles can be informative. The daily variation of the percentiles in Fig. 5 shows that they have a decreasing trend towards the end of the period.

The cumulative distribution of dT_max shown in Fig. 4 was made to study to what extent the service meets the ESA requirements stating that 90% of Class A vessels should be updated every 1.5 h at the Horn of Africa. Excluding the 111 ships using Class B equipment from the calculations, the percentage meeting a 1-h (that actually goes up to 1.5 h because of the $+/-$ 0.5 h bin width) requirement would still not be higher than 20%. As already mentioned under the last two bullets of the list in Section 5.2, the accumulated time gaps also quantify how many ships meet the 1-h and 3-h update requirements: the number in the 0th histogram bin.

The maximum (for number of observations) and minimum (for time gaps) values are indicators of how good the service is at its best.

Concerning the daily results (Fig. 5), all the temporal indicators show a significant variation with an improving trend towards the end of the period. The $n\_hrs\_w\_mes$ went up and the dT_max, $dT > 1h\_accu$ and $dT > 3h\_accu$ went down, the medians expressing this trend even more clearly than the means. Using median values, the number of clock hours a ship is detected ($n\_hrs\_w\_mes$) varies from 13 h to 18 h, the longest time gap in the day (dT_max) from 6.6 h to 4.2 h, the accumulated time of > 1 h gap ($dT > 1h\_accu$) varies from 10.8 h to 6.3 h, and the accumulated time of > 3 h gap ($dT > 3h\_accu$) from 6.0 h to 1.4 h. The median number of observations per day increased from 31 to 35.

The 7-days curves show that the time gap is gradually reduced, whereas the number of observations is only increased for the last two days. Considering the more prominent variation in temporal performance and the small variation in the number of messages and ships, the improvement in temporal performance is most likely due to variations in the coverage of the satellite passes, but it should be kept in mind that the temporal resolution will always be influenced by the actual reporting from the ships.

6.3. Improvement with increasing number of providers

The completeness in number of ships and the update interval are studied from the $P(provset)$ metrics with indicators plotted in Fig. 6 for *provset* 1–5. The number of messages (n_MEST) increases almost linearly with the number of providers. The variations are due to the variation in the number of satellites as well as sensitivity of the receivers, and a data handling strategy on some satellites that reduces redundant information on downlink. The number of ships (n_MMSI) detected increases asymptotically; a smaller increase for each provider is natural since the actual number of ships is finite. The first satellite AIS provider detects 89.2% of the total number of ships in the data from all four satellite AIS providers; the second satellite AIS provider adds 8.6% to that; the third provider adds 1.5%; and the fourth adds 0.7% to reach 100%. Furthermore adding coastal AIS (*provset* 5) results in an increase of 3.5%; typically ships that are turned off part of the day and are difficult to detect by satellites with limited coverage time, whereas the ground-based receivers are always on.

Despite the declining added percentage of ships, the number of messages per ship (n_mes) and the number of observations per ship (n_obs) increase regularly with the number of providers. For n_obs, the first satellite AIS provider contributes with 22.6% to the total n_obs of four satellite providers, the second with 28.6%, the third with 24.7% and the fourth with 24.2%.

For the temporal resolution, each provider added has a significant influence. The number of clock hours with messages ($n\_hrs\_w\_mes$) increased, indicating that each new provider made observations at different hours than the previous. All the indicators for temporal gaps show a reduction for each provider added. Using the median of dT_max as example: One provider gives a value of 8.9 h, using two providers gives a reduction of 2.4 h, the third provider gives a reduction of 0.5 h, and the fourth gives a reduction of 1.2 h – to a final value of 4.3 h. For comparison of *provsets*, the mean gives similar relative results, but the gap values would have been approximately 3 h higher. The reductions as a function of *provset* for the median of $dT > 1h\_accu$ are 5.0 h, 1.4 h, 2.2 h, 3.2 h; and for $dT > 3h\_accu$ they are 4.7 h, 0.6 h, 1.2 h and 1.1 h.

With one provider, the completeness on a daily basis is close to 90% of the ships that are seen by all AIS satellites together, and close to 100% with two providers, which can be adequate for marine spatial planning. The temporal resolution increases significantly also for the third and fourth provider added, but there is still a large gap between the results from 2015 and the requirement of European authorities.

Table 6

Performance indicator values over all ships, using all available satellite AIS as well as coastal AIS, for three different years.

Area	Western Indian Ocean	Gulf of Guinea	Horn of Africa
Time	24–30 Aug 2015	22–28 Mar 2013	16–22 Jan 2012
# Satellites	17 Sat + MSSIS	8 Sat + MSSIS	8 Sat + MSSIS
Mean n_MEST	573,551	395,478	97,853
Mean n_MMSI	1630	2683	1313
Mean values over all ships			
n_mes	352.0	147.4	74.5
n_obs	42.3	24.3	14.3
dT_max (h)	6.7	4.4	6.0
$n\_hrs\_w\_mes$	16.2	14.5	9.3
$dT > 1h\_accu$ (h)	7.7	9.5	14.6
$dT > 3h\_accu$ (h)	4.9	4.9	8.6

6.4. Improvement over the years

To illustrate the variation of the quality of AIS for regional monitoring over a period of 3.5 years, Table 6 shows the mean values of P (*provset* = 5) from Table 5 together with results from two previous campaigns [20]. The trials preceding PMAR-MASE were in the Gulf of Guinea in 2013 and off the Horn of Africa in 2012, the latter covering a similar but not identical area to the one in the present study.

The total numbers of messages and ships (*n_MEST*, *n_MMSI*) do not directly reflect the performance because of the different areas, as well as the changing amounts of shipping over time.

The six mean values that characterise the distribution, however, indicate how the quality of the maritime picture has evolved. The number of messages and observations per ship roughly double from Jan 2012 to Mar 2013, and double again from Mar 2013 to Aug 2015.

The indicators of temporal quality improve less in the last step from March 2013 to August 2015 than they did between January 2012 and March 2013. The longest time gap for a ship during a day, *dT_max*, even deteriorates in the second step. This may be surprising, but can have at least two explanations: The probability of detecting a ship is limited per satellite pass but increases as the observation time increases with more satellites. This has a positive impact on the number of observations of each ship and result in a better track. However, it also makes ships with low probability of detection visible, which results in more ships with long time gaps and associated worse temporal statistics. Another explanation is that the mean value, which is calculated from all the values in the data set, is susceptible to outliers; the occurrence of some ships with one or few observations, from ships that actually are difficult to detect as well as from messages with error in the MMSI (resulting in single messages that give erroneous single observations), influences the mean value more than the median value.

It is important to be aware that in the first case the maritime awareness is improved, even if the temporal statistics have suffered. If there are many occurrences of erroneous MMSI's, it is reason to check carefully for these, and thereby improve the quality.

7. Conclusions

The study presents properties of satellite-based AIS services with respect to coverage and revisit time and presents methods for calculating performance metrics for a maritime picture made from satellite AIS data. The methods have been applied to a data set from four satellite AIS providers and one provider of coastal AIS, from the Indian Ocean in August 2015. The results show how well ships were detected and tracked, how the quality of service depends on the number of providers used, and what statistical measures are appropriate to characterise the maritime picture.

Regarding completeness on a daily basis, one satellite AIS provider (3 satellites) detected about 90% of the ships detected by all satellites (in total 17 satellites), the second provider (4 more satellites) increased the ratio to 98%, and the last two providers added approximately 1% each. Adding coastal AIS, even if of a much more limited geographical coverage, but of the presumably busiest areas in the region, revealed the presence of 3.5% more ships, increasing the total to 1630.

Unlike the completeness that increases asymptotically with additional providers, the temporal resolution increased steadily. Typically the observation gaps were reduced by more than one hour for each additional provider, but still gaps caused by lack of satellite coverage remain even with all satellite data. Adding coastal AIS improved the temporal statistics beyond the results for all satellites. The percentage of ships meeting requirements for update intervals of 1 h and 3 h is only 20% and 40%, respectively, which is low compared to the operational requirements at the Horn of Africa proposed by European authorities responsible for maritime affairs and fisheries.

Using data from all satellite AIS providers, the daily temporal indicators had a significant variation with an improving trend towards the end of the 7-days period. The median value of the longest time gap was reduced from 6.6 h to 4.2 h, whereas the median number of observations per day increased from 31 to 35. The 7-days curves show that the time gap is gradually reduced, whereas the number of observations is only increased for the last two days. Hence, the variation can be attributed to a more favourable temporal distribution of the satellite passes over the day. A real constellation of 17 satellites, optimised for shared ground coverage, would have better temporal performance than what is obtained here with the same number of satellites from four providers.

To find appropriate metrics for the ship observations and tracks in terms of update interval, six indicators and their distributions, characterised by 28 statistical measures, were explored. It is found that the distribution of each of the indicators over all ships is very broad and asymmetric. This means that in the maritime picture, some ships can be tracked very well, some not at all, and everything in between. Using the 10- and 90-percentiles as limits, gaps between 0.5 h and 20 h should be considered normal for the service in the Indian Ocean in August 2015.

The three most useful indicators to characterise the temporal quality of service are:

- Longest time gap between messages of each ship;
- Total accumulated time that the most recent message was more than 1 hour old;
- Total accumulated time that the most recent message was more than 3 hours old.

A significant difference is found between the mean and median values of the distribution of the quality of service over all ships: Using all AIS data, the mean value of the longest gap time is 6.7 h, while its median is 4.3 h.

Due to the skewed distributions the mean and standard deviation, which are the statistical measures that most people are familiar with, are not well suited to characterise the distribution. In such cases the median – representing the value in the centre of the distribution – is generally considered to be the best representative of the central location of the data. However, to compare the quality of service of different AIS provider configurations, the change of the mean has a similar behaviour as the change in the median, and may be used to study the variations.

The indicator of the central tendency of the quality of service should at least be accompanied by an indicator of the spread. With the standard deviation unfit to characterise the spread, the minimum, maximum, and 70- and 90-percentile were explored. Whereas the minimum and maximum simply show the extreme values, the percentiles characterise the spread as well as the percentage of ships for which a certain performance is achieved well. Using all AIS data, the 70- and 90-percentiles of the longest time gap between two messages from each ship are 6.7 h and 19.5 h, respectively.

In addition to serving as metrics for the quality of service the 90-percentile (or other percentage at the high end) could be particularly useful as a threshold to limit the number of ships to those that may have turned off their AIS and therefore can be worth investigating.

Acknowledgements

Thanks to the Norwegian Coastal Administration (NCA) for providing satellite AIS data, and the U.S. Navy and the Volpe Centre of the U.S. Department of Transport for providing coastal AIS data, free of charge. Thanks also to the commercial providers exactEarth, SpaceQuest, and ORBCOMM/LuxSpace for their support to the project.

Funding source

The data used were collected in the project on Piracy, Maritime Awareness and Risks (PMAR) that was carried out by the Joint Research

Centre for the Indian Ocean Commission under the Program to Promote Regional Maritime Security (MASE) in the Eastern and SouthernAfrica/ Indian Ocean region, funded under the 10th European Development Fund (contract FED/2014/346-721).

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