FastTrack publication

Bull Mar Sci. 92(1):75–103. 2016
http://dx.doi.org/10.5343/bms.2015.1034

review

Conservation science and policy applications of the marine vessel Automatic Identification System (AIS)—a review

MD Robards [1*]
GK Silber [2]
JD Adams [2]
J Arroyo [3]
D Lorenzini [4]
K Schwehr [5]
J Amos [6]

[1] *Wildlife Conservation Society, Arctic Beringia Program, Fairbanks, Alaska 99775.*

[2] *Office of Protected Resources, NOAA Fisheries, Silver Spring, Maryland 20910.*

[3] *United States Coast Guard, Office of Navigation Systems, Washington, DC 20593.*

[4] *Space Quest, Fairfax, Virginia 22030.*

[5] *Google, Mountain View, California 94043.*

[6] *SkyTruth, Shepherdstown, West Virginia 25443.*

* *Corresponding author email: <mrobards@wcs.org>.*

Date Submitted: 20 May, 2015.
Date Accepted: 15 October, 2015.
Available Online: 15 January, 2016.

ABSTRACT.—The continued development of maritime transportation around the world, and increased recognition of the direct and indirect impacts of vessel activities to marine resources, has prompted interest in better understanding vessel operations and their effects on the environment. Such an understanding has been facilitated by Automatic Identification Systems (AIS), a mandatory vessel communication and navigational safety system that was adopted by the International Maritime Organization in 2000 for use in collision avoidance, coastal surveillance, and traffic management. AIS is an effective tool for accomplishing navigational safety goals, and by doing so, can provide critical pre-emptive maritime safety benefits, but also provides a data opportunity with which to understand and help mitigate the impacts of maritime traffic on the marine environment and wildlife. However, AIS was not designed with research or conservation planning in mind, leading to significant challenges in fully benefiting from use of the data for these purposes. We review present experiences using AIS data for strategic conservation applications, and then focus on efforts to ensure archived and real-time AIS data for key variables reflect the best available science (of known limitations and biases). We finish with a suite of recommendations for users of the data and for policy makers.

Maritime vessel activities around the globe have frequently resulted in conservation impacts to wildlife; directly impacting individuals or groups of animals through disturbance, fatal strikes, and introduction of pathogens; or impacting habitats through anchoring (especially on corals), introduction of invasive species, air emissions, noise, and fuel spills (e.g., Laist et al. 2001, Bax et al. 2003, Burgherr 2007, Corbett et al. 2007, AMSA 2009, Silber et al. 2012, Richardson et al. 2013). Despite the diversity and severity of potential conservation impacts, spatial data for global vessel traffic has, until recently, been sparse or overly generalized, limiting an ability

Table 1. Global shipping fleet data for 2013 in thousands of deadweight tonnage (DWT; UNCTAD 2013).

	Vessel DWT (1000s)	Percent of total fleet	Percent change since 2012
Oil Tankers	490,743	30.1	4.5
Bulk Carriers	684,673	42.0	9.9
General Cargo	80,345	4.9	−0.6
Container	206,577	12.7	4.9
Other*	166,445	10.2	−0.1

* Includes: gas carriers; chemical tankers; offshore ferries and passenger ships; and some others less common types including propelled seagoing merchant vessels of 100 gross tonnage and above.

to understand and respond to both threats and impacts. As modernization and expansion of vessel traffic occurs (Table 1), there are opportunities to improve safety situations through automatic vessel monitoring (e.g., Aase and Jabour 2015, Felski et al. 2015), but also opportunities for understanding and responding to environmental threats, which is the topic of the present review.

Maritime transport accounts for approximately 90% of all world trade, including 60% of the deliveries of the world's oil and fuel supplies (UNCTAD 2013). Size and speed of the largest vessels are increasing—container ships can now be in excess of 400 m long, travel at up to 25 kt, and carry >20,000 t of fuel alone (Gray 2013, Fields 2014). Marine transportation of people has also escalated, with fast-passenger ferries increasingly used in coastal areas, and cruise ships of the latest Oasis Class that are capable of carrying up to 6000 passengers. In addition, there are an estimated 2.1 million powered fishing vessels around the globe (FAO 2009). Evolving industries are expanding markets for certain products (e.g., Liquefied Natural Gas), development of new or expanded port facilities is common, and with diminishing high latitude sea ice, Arctic shipping routes are becoming more routinely used (AMSA 2009).

Despite increases in activity and vessel size, overall vessel accidents have declined, and the most egregious to the environment—oil spills—have declined significantly (Burgherr 2007, Fields 2014). Nevertheless, 84% of accidents can still be attributed to human error, and with larger vessel sizes, the potential risks to the environment and people grow (Harati-Mokhtari et al. 2007). Large numbers of vessels are registered in countries with lax enforcement of environmental or safety regulations, that while reducing operating costs or avoiding host country regulations, are linked with correspondingly poorer safety records (Alderton and Winchester 2002, Hoffmann et al. 2005).

Quantification of the impacts of vessel traffic to wildlife and the environment lags well behind what is required for informing effective conservation policy. However, over the last decade, our understanding and knowledge of vessel operations in relation to wildlife and the marine environment has been aided by data obtained from vessel tracking systems. The most widely used system being the maritime very high frequency (VHF) Universal Automatic Identification System, or AIS, which originated as a concept in the mid-1990s. Development of AIS technology was led by a number of countries within various organizations, including the International Maritime Organization (IMO), the International Telecommunication Union (ITU), the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), and the International Electrotechnical Commission (IEC). Subsequent promulgation of regulations mandating its use by the IMO were made under the auspices of the Safety of Life at Sea Convention (SOLAS). Synthesis of information from the system now produces a relatively rich data stream describing ship traffic, which is shared in real-time among users. Further, it is used between mariners and other marine interests, including those with a conservation perspective, vastly increasing our Maritime Domain Awareness (IALA 2005, Tetreault et al. 2010, Carson-Jackson 2012, Shelmerdine 2015).

As implemented under SOLAS, AIS was designed for vessel safety, to support ship-to-ship collision avoidance, a means for littoral States to obtain information about a ship and its cargo, and as a tool in ship-to-shore Vessel Traffic Services (VTS) (IMO MSC74: 69). However, given the potential value of AIS to conservation issues and the IMO's imperative to "improve the safety of navigation by assisting in the efficient navigation of ships, *protection of the environment*, and operation of VTS" (IMO MSC74: 69; emphasis added), the system's functionality toward achieving environmental protection goals can and should be improved (Aarsæther and Moan 2009, Last et al. 2014).

The Automatic Identification System

Background to AIS

Who Uses AIS?

AIS was designed as a mandatory collision avoidance system for sea-going vessels—an opportunity to identify and be identified by others (radar provides detection, but not identity and intentions). In 2000, IMO revised the SOLAS Chapter V, Regulation 19 (covering all navigational equipment to be carried on board different types of ships) to require AIS, and that it be capable of providing information about the ship to other ships and to coastal authorities. As of 1 July, 2008, all ships ≥300 gross tonnage engaged on international voyages, cargo ships ≥500 gross tonnage not engaged on international voyages, tankers, and all passenger ships irrespective of size use AIS. Most IMO regulated SOLAS ships, approximately 60,000, are required to be outfitted with an AIS Class A device (Table 2), which must be in operation at all times except where international agreements, rules, or standards provide for the protection of navigational information. In 2006, AIS Class B transceivers were introduced, as a lower cost, interoperable, yet slightly less capable alternative for non-mandated vessels, such as fishing boats, recreational boats, small domestic ships, and even artisanal craft (Table 2). Many of these users have opted to have AIS Class B transmitters at their own volition or at the request of owners, allowing vessels to be better detected, and, to detect others, without more expensive radar systems. While Class B systems provide a more limited functionality and lower power than Class A, the rapid overall adoption of AIS around the world has supported rapid adoption of Class B on many vessels where Class A is not required.

Different countries or regions are developing additional AIS requirements. For example, while operating on the navigable waters of the United States, all self-propelled commercial vessels ≥19.8 m, or towing vessels ≥7.9 m and over 600 horsepower, as well as dredges and vessels moving dangerous cargo must carry AIS (46 US Code § 70114). Elsewhere, the European Commission has required the entire fishery fleet >15 m in length to install AIS Class A transmitters since 31 May, 2014 (Shelmerdine 2015). Collectively, these types of regulations continue to expand the suite of vessels carrying AIS, and thus the value of the system for conservation planning for a wide array of applications.

Table 2. Automatic identification system (AIS) Class A vs Class B self organizing (SO) and carrier-sense (CS) transmitters. ETA = estimated time of arrival; IMO = International Maritime Organization; SOLAS = Safety of Life at Sea Convention; TDMA = Time Division Multiple Access.

	Class A	Class B/SO	Class B/CS
Vessels carrying AIS	Mandated per SOLAS and other administrations (e.g., USA)	Permissible in lieu of Class A or voluntarily used	Permissible in lieu of Class A or voluntarily used
Data input	Data entry via minimum keyboard display or electronic charting system	Optional	Optional
Broadcast mode	Self-organizing TDMA (SOTDMA)	Self-organizing TDMA (SOTDMA)	Carrier-sense TDMA (CSTDMA)
Position reporting rate when underway	2–10 s based on speed and course change	5–30 s based on speed	Every 30 s
Position reporting rate when anchored or moored	Every 3 min	Every 3 min	Every 3 min
Static data reporting rate	6 min	6 min	6 min
Power	12.5 w / 2 w (low-power)	5 w / 2 w (low-power)	2 w
Safety text messaging	Receives and transmits	Receives and transmits	Transmit optional, and only with non-alterable, pre-configured messages
Application specific messaging	Receives and transmits; transmits on up to 3 slots	Receives messages; transmits on up to 3 slots	Receiving is optional; cannot transmit
Data	All AIS data	No rate of turn, navigation status, destination, ETA, draft, or IMO number	No rate of turn, navigation status, destination, ETA, draft, or IMO number

How Does AIS Function?

AIS autonomously and continuously transmits messages containing static data (vessel identification data such as name, call sign, IMO number, type, and dimensions), dynamic navigation sensor data (i.e., vessel position, speed over ground, course over ground, heading, rate of turn), and manually inputted voyage-related data (i.e., navigational status, current draught, destination, and ETA—mostly entered by the Master or Officer of the Watch) (IMO 2003). The system provides vessel identification, regardless of whether dynamic and voyage related data are available. All data are linked to a Global Navigation Satellite System (GNSS).

Overall, there are 27 top-level message types, which are used to convey information via the Very High Frequency-Frequency Modulated (VHF-FM) AIS signals (defined in International Telecommunication Union recommendation M.1371-5), on one or on two worldwide dedicated channels (Ch.87B – 161.975 MHz and Ch.88B – 162.025 MHz). AIS, as with any VHF-FM system, operates on line of sight, thus has a typical range to surface receivers of about 13–39 km, depending on topography, atmospheric conditions, receiver type, and other factors. These data are decoded upon reception and shown to the user textually, but, is also made available to external devices, which can process the data and portray them in graphical form, and/or integrate them into other systems (e.g., radar, electronic chart systems or plotters, geographic information system [GIS]). The AIS VHF Data Link (VDL) is capable of handling up to 4500 messages per minute. To maximize VDL efficiency, AIS transceivers (AIS Class A and B-SO) rely upon—and unique to AIS—a Self-Organizing variant of the Time Division Multiple Access (SOTDMA) packet radio scheme. SOTDMA ensures all AIS transmissions are "self-organized" such that the majority of these slots are reserved for the use of one station at a time, mitigating slot collisions (garbling).

Differently, Class B-CS rely on a Carrier Sense variant of TDMA (CSTDMA), that only transmit if they find free available slots, sometimes also called "polite AIS."

Networks of receivers along coastlines provide local coverage, and in some places receivers are placed on buoys, oil platforms, aircraft, or autonomous vehicles to supplement these networks. However, since 2008, Low Earth Orbiting (LEO) satellites have been added to the mix of receiving platforms and increasingly provide global data. This includes new types of pico- (0.1–1 kg), nano- (1–10 kg), and micro-satellites (10–100 kg), such as those used by SpaceQuest®, Orbcomm®, and exactEarth®, that each can pick up more than 4,000,000 messages from more than 130,000 unique vessels (about 35,000 are class B) each day (SpaceQuest, unpubl data; Orbcomm, unpubl data).

Land-based receivers provide real-time data, but are limited by their coverage to the network of base stations and vessels; conversely, satellite-based receivers can provide near global coverage, but data are frequently time-delayed. Satellite AIS coverage has rapidly increased, but is still challenged by a relatively small constellation of satellites, limited number of ground stations to receive data, their ability to pick up a relatively weak signal designed for earth surface use, and data integrity given a satellite's footprint and overlapping transmissions. Nevertheless, new efforts by private organizations, such as exactEarth and Harris Corporation's deployment of 58 hosted payloads on the Iridium NEXT constellation promises persistent global coverage, near real time connectivity (revisits at <1 min), and reliable detection of both Class A and Class B AIS messages.

Who is Not Included in AIS Data?

International and national regulations make AIS carriage mandatory for many seagoing vessels, and many others have opted to use it voluntarily (often Class B) for insurance, convenience, security, and/or safety reasons (e.g., maritime tourist industry). Nevertheless, it still represents a small number of all the vessels in the world, and does not include most small fishing vessels, recreational boaters, inland vessels, warships, and naval auxiliary vessels.

Third-Party Use of AIS Data

AIS was not designed or intended to be an archive, public medium, or research application; all these purposes transcend the IMO's primary goal of vessel safety (McIntyre et al. 2007). In fact, some prominent entities (e.g., INTERTANKO, INTERCARGO, BIMCO, ICS) have sought to limit public access to data. At the 79th meeting of the IMO's Maritime Safety Committee (MSC) in 2004, concerns were raised about the freely available vessel information from the AIS system that was available online, and how this could be detrimental to the safety and security of ships and port facilities. The IMO condoned the practice of releasing data in the public domain, but governments have not moved to restrict its availability.

Difference with Respect to Other Vessel Tracking/Monitoring Systems

AIS by design, is universal and operates on an autonomous, continuous, open, and mostly non-proprietary protocol, which does not require shore-side infrastructure for its operation. However, it may be confused with several vessel-monitoring systems that use similar technology, or include AIS as one component in a suite of tracking tools, many of which are also useful to maritime safety and consequently environmental conservation.

- Vessel Monitoring Systems (VMS) principally relay vessel names, locations, and times within specific areas. Vessels engaged in certain activities, such as commercial fishing, may be required to carry VMS equipment as a condition of obtaining a permit to fish so regulatory agencies might track their operations. VMS generally uses various radio technologies and involves proprietary data. Several authors have developed conservation applications using VMS data (e.g., Gerritsen et al. 2013, Gonzalez-Mirelis et al. 2014).
- Vessel Traffic Services (VTS) are used to ensure safety of navigation and flow of traffic around ports. They typically use multiple sensors to locate, advise, and manage vessels in confined areas. AIS, which can be used to verify the identification of radar targets and track vessels in non-radar coverage areas, may be a valuable component of a VTS (e.g., Tetreault et al. 2010).
- Monitoring, Control, and Surveillance (MCS) is similar to VMS in that it is used to monitor a specific maritime sector. It is also similar to a VTS because mandatory AIS carriage is frequently required as part of a larger suite of tools used to monitor fishing vessels in National and High Seas areas (e.g., Le Gallic and Cox 2006).
- Long-Range Identification and Tracking (LRIT) was adopted by the IMO in 2006 and is mandatory for most seagoing ships, passenger vessels, and mobile offshore drilling units. LRIT is a daily reporting system (4 d^{-1}), that relies upon worldwide private communication service providers to relay these reports to LRIT data centers, thence to the LRIT data exchange, which provides these reports solely to national administrations that are entitled to the reports because the vessel is either of their flag, en-route to a port within their nation, or is transiting its coastal waters. These same entitled administrations can contract with LRIT Data Exchange to poll these vessels at a greater rate (i.e., 180, 60, 30, or 15 min). LRIT is protected and not intended to be shared beyond administrations and search and rescue coordination centers.

Current Use of AIS in Conservation Research Applications

AIS data have at least three important applications in conservation science: (1) describing baseline vessel use of a maritime area; (2) assessing or modeling actual or potential environmental impacts; and (3) monitoring environmental compliance. Illustrative examples of each of these applications are provided below and in Table 3.

Describing Baseline Vessel Use of a Maritime Area

Vessel Routing and Operations

Problem.—An understanding of routine vessel operations has wide applicability as a precursor to assessing conservation risk or impacts. Through AIS, movements of individual or groups of vessels can now be linked to attributes such as vessel type, speed, dimensions, or status, and where, how often, and how far they transit. These data can then be coupled with environmental factors such as meteorological and oceanographic conditions, or areas of conservation risk such as whale aggregations.

Application Examples.—Robards (unpubl) assessed seasonal movements of different vessel types along the Great Circle Route in the North Pacific Ocean, particularly as it relates to critical wildlife habitats of the Aleutian Islands and intervening passes

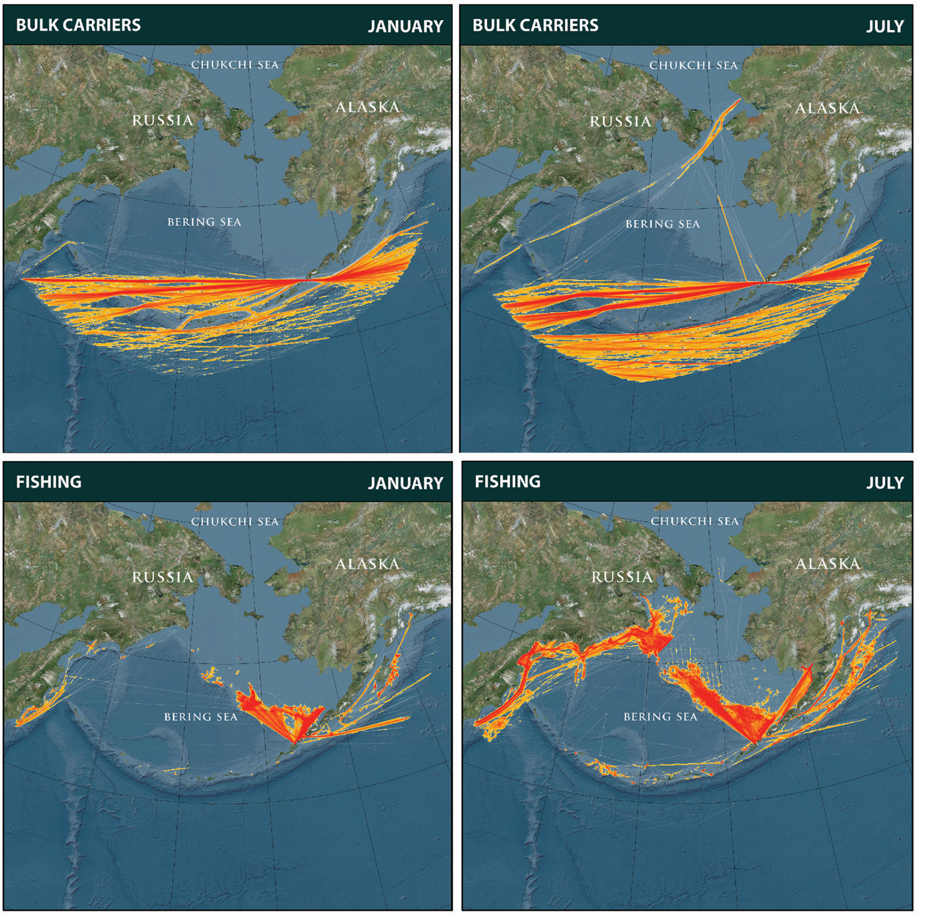

Figure 1. Top: Seasonality of bulk carrier vessel traffic in the Aleutian Archipelago, Bering, and Chukchi Seas. Summer (July) traffic sees less traffic in the central Aleutian arc and greater travel into the Chukchi Sea (primarily here to the Red Dog mine). Bottom: Seasonality (January and July) of fishing vessel activity in the Aleutian Archipelago, Bering, and Chukchi seas.

(Fig. 1); Shelmerdine (2015) conducted a similar assessment in the Shetland Islands off Scotland. Willems et al. (2009) went several steps farther in their exploration of visualization techniques that can depict the dynamic attributes of vessels travelling in and out of Rotterdam, Netherlands (Fig. 2). Through creative use of density coverages, they were able to depict vessel lanes, anchoring areas, and potential areas of risk under different weather conditions. Calder and Schwehr (2009) used AIS data to provide a statistical characterization of vessel traffic at Norfolk's port (Atlantic coast of United States), including transit locations, trip destination and duration by vessel category, as well as type of traffic, physical dimensions, and intensity of activity.

Underwater Noise

Problem.—Underwater noise emanating from vessel traffic and industrial activities is a rapidly developing area of conservation concern due to the demonstrated adverse effects on various living marine organisms, including marine mammals (Richardson et al. 2013). AIS provides a tool for helping understand underwater soundscapes

Table 3. Examples of current Automatic Identification System (AIS) data usage for conservation[1]. ?? = Unreported information.

Project	Receiver station	Number of vessels	Ship type reported	Location	Data subset?[2]	Data errors reported?	Errors corrected?[3]	Source
Baseline Data								
Vessel behavior	Ground	??	Yes	USA, Atlantic	Yes	Yes	Algorithm	Calder and Schwehr 2009
Visualization of vessel behavior	??	??	Yes	Netherlands	Yes	Yes	Yes	Willems et al. 2009
Visualization of vessel behavior	Ground	??	Yes	Scotland	No	Yes	Yes	Shelmerdine 2015
Ocean noise fields	Ground	541	Yes	USA, Atlantic	Yes	Yes	Manual	Hatch et al. 2008, 2012
Sound exposure	??	Individual	Yes	Scotland	Yes	Yes	Yes	Merchant et al. 2012
Cumulative noise	??	??	No	Pacific NW	No	No	No	Erbe et al. 2012
Radiated noise	Ground	??	Yes	USA, Pacific	No	Yes	Yes	McKenna et al. 2012
Sound exposure	Ground	??	Yes	Scotland	Yes	No	No	Merchant et al. 2014
Risk Assessment								
Collisions with whales	Ground	??	No	USA, Pacific	Yes	Yes	Yes	Redfern et al. 2013
Collisions with whales	Ground	892	Yes	Panama	Yes	No	No	Guzman et al. 2013
Collisions with whales	Ground	502	Yes	USA, Atlantic	No	No	No	Wiley et al. 2011
Collisions with whales	Ground	??	No	Canada, Atlantic	No	Yes	Yes	van der Hoop et al. 2012
Collisions with whales	Ground	26	Yes	USA, Alaska	Yes	No	Yes	Webb and Gende 2015
Collisions with whales	??	767	Yes	New Zealand	No	No	No	Constantine et al. 2015
Collisions with whales	Satellite	??	Yes	Sri Lanka	No	No	No	Priyadarshana et al. 2015
Introduction of non-native species	Ground	>200	Yes	Scotland	Yes	Yes	Yes	Shucksmith and Shelmerdine 2015
Exhaust emissions	Ground	9,497	Yes	Baltic	No	Yes	No	Jalkanen et al. 2009, 2012
Emission inventory	Ground	499	Yes	Hong Kong	Yes	No	No	Ng et al. 2013
Projected emissions	Satellite/ground	133,535	Yes	Arctic	No	No	No	Winther et al. 2014
Emissions, air quality, visibility	Ground	225	Yes	USA, Alaska	Yes	No	Manual	Mölders et al. 2013
Modeling behavioral change	Ground	??	Yes	Scotland	No	No	No	New et al. 2013[4]

Table 3. Continued.

Project	Receiver station	Number of vessels	Ship type reported	Location	Data subset?[2]	Data errors reported?	Errors corrected?[3]	Source
Compliance								
Efficacy of a voluntary area	Ground	??	Yes	USA, Atlantic	No	Yes	Yes	Vanderlaan and Taggart 2009
Collisions with whales	Ground	??	Yes	USA, Atlantic	Yes	Yes	Yes	Conn and Silber 2013
Whale protection measures	Aircraft	4,684	Yes	USA, Atlantic	Yes	No	No	Lagueux et al. 2011
Oil discharge monitoring	Satellite	??	No	Europe	Yes	No	No	Ferraro et al. 2010

[1] Citations are examples specifically focused on conservation applications; those focused on improvement of AIS data for navigation alone as part of the Maritime Domain Awareness literature are not included (for example, see: Aase and Jabour 2015; Felski et al. 2015).

[2] Some data removed from the overall AIS stream to address a specific question.

[3] Includes use of external data to populate fields (e.g., vessel dimensions).

[4] Uses Lusseau et al. (2011) for data.

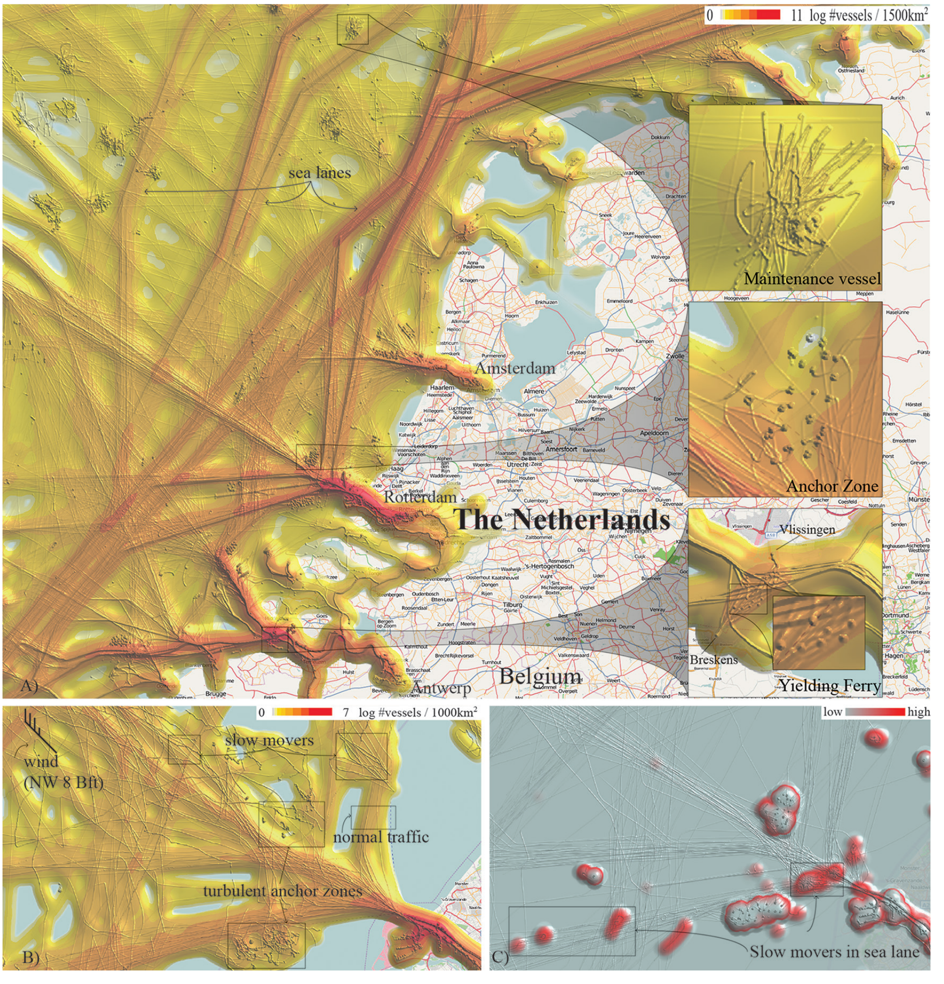

Figure 2. (A) Vessel density on the Dutch coast based on AIS data and attributes of vessel behavior (reproduced from Willems et al. 2009 and used with permission). Trajectories are for a week covering 160,000 km^2. The anchor zone and yielding ferry inserts are renderings of a day. (B) Vessel density of a stormy day: northwest wind with force 8 on the Beaufort scale change the movement patterns of vessels entering and leaving Rotterdam. (C) Vessel density of areas where vessels sail <3 kt during calm weather can be overlaid on shipping lanes to show areas of potential risk.

based on vessel use and type. AIS may also be used to identify vessels engaged in geological and geophysical survey activity or military activities, all of which can be a source of acoustic noises that have been linked to decreased fisheries catch rates (Engås et al. 1996), marine mammal migratory disruptions (Castellote et al. 2012) and stranding events (Southall et al. 2013), and even damage to marine invertebrates (Guerra et al. 2004).

Application Examples.—In an innovative study involving simultaneous and long-term AIS vessel tracking and underwater sound monitoring of vessels in waters off southern California, McKenna et al. (2012) quantified low-frequency noise relative to ocean-based commercial shipping trends. Because the study period (2007–2010) spanned the period of a global economic downturn, as well as regulatory events affecting shipping in the region, the authors were able to quantify a net reduction of 12 dB in noise emanating from reduced shipping levels (established from AIS). They concluded that a reduction of one ship transit per day would result in a 1 dB decrease in average noise for the study area.

In two related studies (Hatch et al. 2008, 2012), AIS was used to quantify the contribution of vessel traffic to ambient underwater noise in the Stellwagen Bank National Marine Sanctuary (USA), particularly as it related to noise exposure for North Atlantic right whales (*Eubalaena glacialis* Müller, 1776). The authors concluded that exposure to high levels of ship-generated noise may compromise right whale intra-specific vocal communications. Similarly, Merchant et al. (2014) addressed baseline noise levels and impacts to Atlantic bottlenose dolphins (*Tursiops truncatus* Montagu, 1821) in the Moray Firth Special Area of Conservation off Scotland. These authors raised the additional issue that while their study confirmed that most vessel noise in their area was attributable to AIS-carrying vessels, in areas away from commercial activity; non-AIS vessel traffic may be of greater concern. They assessed the potential impact of these other vessels by using AIS in conjunction with time-lapse photography.

Assessing, Modeling, and Mitigating Actual and Potential Environmental Risks

Interactions with Whales

Problem.—Establishing areas where large cetaceans and vessels are likely to overlap in space and time is a critical step to understanding and reducing vessel strikes. However, assessment is challenging given that the detection and avoidance of vessels by whales, where it occurs, appears to vary with ship size and level of radiated sound (Jahoda et al. 2003, Aguilar Soto et al. 2006), as well as the current behavior and species of whale (Richardson and Würsig 1997, Weilgart 2007).

Application Examples.—Guzman et al. (2013) assessed the overlap between commercial vessels transiting to and from the Panama Canal and wintering Southern Hemisphere humpback whales (*Megaptera novaeangliae* Borowski, 1781). Using filtered AIS data (to remove stationary and some locally operating vessels) and data from 15 tagged whales, the authors demonstrated significant overlap between whales and vessels, and offered a preferred shipping route along with recommendations for speeds below 10 kt. This study has resulted in the establishment of new IMO-adopted Traffic Separation Schemes on both Atlantic and Pacific ocean sides of the Panama Canal, and a seasonal (1 August–30 November) speed recommendation of not >10 kt (IMO COLREG.2/Circ.65; 23; IMO SN.1/Circ.326; 23 May, 2014). A similar situation for the vessel routes entering Boston Harbor has been well described (Fig. 3; Wiley et al. 2013). In Southeast Alaska, Webb and Gende (2015) used AIS data for large cruise ships to assess where their presence and speed represented the greatest threat to summering humpback whales.

Introduction of Non-native Species

Problem.—The introduction of non-native species as a result of maritime traffic around the globe is an increasing problem (Molnar et al. 2008). AIS offers an opportunity to help map pathways for these introductions.

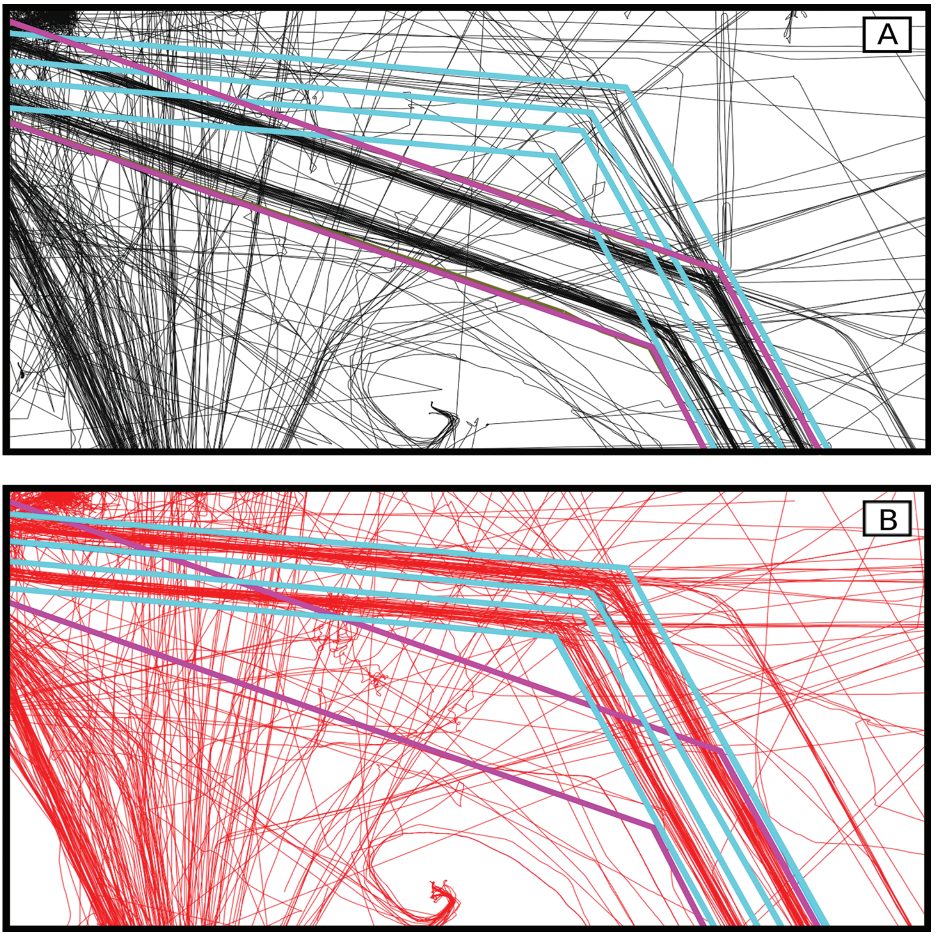

Figure 3. (A) Vessel traffic pattern as seen via AIS prior to shift of the Boston Traffic Separation Scheme (1–10 June, 2007). B) Vessel traffic pattern as seen via AIS after the shift of the Boston Traffic Separation Scheme (1–31 July, 2007). The original Separation Scheme is depicted in pink and the new Separation Scheme in blue. AIS confirmed general compliance by vessel traffic with the new Boston Traffic Separation Scheme.

Application Example.—Shucksmith and Shelmerdine (2015) establish biofouling as a key source of non-native species. They used AIS data to both map the temporal and spatial patterns of vessel activity around the Shetland Islands of Scotland, and the source ports for the vessels passing close to the islands.

Air Emissions

Problem.—Air quality issues associated with vessels are now well described in the conservation literature. Emissions can be modeled based on voyage data collected from AIS (e.g., location, speed, vessel type, operation mode) and the ships' engine/emissions characteristics, which can be linked to a particular vessel via the identification fields in AIS data.

Application Examples.—Jalkanen (2009, 2012) developed a model (STEAM2) that allows for incorporation of vessel routing, speed, engine load and configuration, fuel sulfur content, abatement, and ocean waves for modeling the spatial extent of emissions. Via AIS data, Ng et al. (2013) found container vessels were the top emitters in 2007 in Hong Kong, contributing about 80% of air emissions, while Winther et al. (2014) concluded that fishing vessels were the biggest emitters in the Arctic. Mölders et al. (2013) integrated AIS data for cruise ships with a Weather Research and Forecasting model and chemistry to assess the impact of management actions on air quality and visibility within Glacier Bay National Park and Preserve (Alaska). Finally, Mjelde et al. (2014) demonstrated a framework for the Arctic and British Columbia (Canada) coast for assessing environmental impacts from air emissions and other environmental risks.

Monitoring Environmental Compliance

Ensuring Compliance with Protected Areas and Speed Restrictions

Problem.—Assessing, and then ensuring compliance, with conservation-oriented rules or regulations is an essential component of their effectiveness (e.g., Keane et al. 2008).

Application Examples.—One of the greatest threats to the recovery of the endangered North Atlantic right whale is collision with ships (or "ship strikes"). The US National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) sought to reduce the threat, including issuing a final rule (73 Federal Register 60173, October 2008) that requires vessels >19.8 m in length to travel at 10 kt or less at certain times and locations where whales occur (termed "Seasonal Management Areas", or SMA). NMFS also initiated a program whereby temporary zones called "Dynamic Management Areas" (DMA) could be established in areas in which right whales are observed outside SMAs. Within the DMAs, vessels are requested (but, not required) to either navigate around the zone or travel through it at ≤10 kt. These temporary zones allow for management measures that are tied directly to the known, but perhaps transitory, presence of right whales, and provide a means to establish areas affecting vessel operations that are smaller (in area) and shorter (in duration) than seasonal management measures.

Using AIS data, Lagueux et al. (2011) evaluated compliance with the voluntary and mandatory vessel routing and speed rules for North Atlantic right whales, finding higher compliance with speed recommendations under mandatory rules, whereas high compliance on recommended routings was possible with only voluntary rules. Silber et al. (2014) used AIS to assess compliance with vessel speed restrictions in SMAs, suggesting citations and fines have a greater influence on compliance than a suite of outreach methods. Trips by cargo vessels exhibited the greatest change in behavior followed by tanker and passenger vessels. A study carried out by Wiley et al. (2013) in the Stellwagen Marine Sanctuary resulted in the introduction of a Whale Alert system based on AIS that monitors vessel behavior (e.g., speed and routing) through the sanctuary. Correspondence with vessel companies exhibiting transgressions to rules has resulted in much improved compliance (Wiley et al. 2013). Similarly, in Glacier Bay National Park (Alaska), AIS is used to encourage cruise ships to maintain ≤10 kt when in designated "whale waters," and achieved 100% compliance (Ed Page, Marine Exchange of Alaska, pers comm).

Monitoring of Illegal Oil Discharge

Problem.—Illegal discharges of oil, bilge, and other vessel fluids are a persistent issue with maritime traffic.

Application Examples.—Automatic detection of oil on water via remote sensing (e.g., Synthetic Aperture Radar—SAR) can be linked to potentially offending vessels via AIS (Ferraro et al. 2007, 2010, Schwehr and McGillivary 2007, Zhao et al. 2014). This addresses the major shipping convention—International Convention for the Prevention of Pollution from Ships (MARPOL)—through an AIS application. Private organizations such as SkyTruth and SpaceQuest have publicly demonstrated this approach (Fig. 4; SkyTruth 2012) and have worked together to automate such efforts, which may be particularly useful in remote areas like the Arctic or High Seas.

Monitoring Illegal, Unreported, and Unregulated (IUU) Fishing

Problem.—"The Dark Fleet" (Windward 2014) can be better assessed via AIS for illegal fishing activity, particularly in international offshore waters.

Application Examples.—Despite issues over unsecured information from AIS and the fishing industry's desire for confidentiality over fishing areas, a European Commission directive requires fishing vessels >15 m in length to operate AIS equipment, in part to mitigate the 48% of vessels that do sink, do so as a result of collisions with these fishing vessels (Detsis et al. 2012). Such mandatory AIS carriage supports safety as well as more effective monitoring, control, and surveillance efforts, with non-AIS carriers capable of being automatically detected by SAR (Le Gallic and Cox 2006, Detsis et al. 2012, Gjerde et al. 2013). Several efforts are now underway to automate linkages between AIS and SAR around the world to monitor vessels (Detsis et al. 2012).

Entities such as Pew Charitable Trusts and SkyTruth (in collaboration with Analyze, Google, and SpaceQuest) are automating the detection and mapping of vessel behaviors of interest, including fishing. Analyses of vessel movement based on AIS data alone suggest there are unique motion signatures associated with vessels engaged in fishing activities. Using an algorithm developed by machine learning and validated by fishing effort and catch information, AIS data across vast swathes of the ocean can be assessed, with vessels assigned a fishing activity score. The AIS-detected "fishing events" can then be displayed on an interactive web-accessible map, highlighting those areas where fishing activity is taking place; the Global Fishing Watch project exemplifies this approach (http://www.globalfishingwatch.org/). As fishing vessels are increasingly required to use AIS, and as new remote sensing efforts are used to detect illegal fishing (Elvidge et al. 2015), the size of the "dark fleet" will steadily shrink, allowing fisheries officials to more effectively focus their monitoring and inspection efforts in time and space.

AIS analysis, when combined with fishing license and other information, can also uncover IUU fishing activity and support the direct enforcement of fishing laws, as recently demonstrated by SkyTruth and Pew Charitable Trusts in the waters of Palau (Joyce 2015). As satellite AIS coverage improves, near-real-time enforcement support will become operational, although increased awareness of this capability may spur a reduction in AIS use by vessels that engage in illegal activity, but, in turn ensure their inspection when monitors and regulators are on scene.

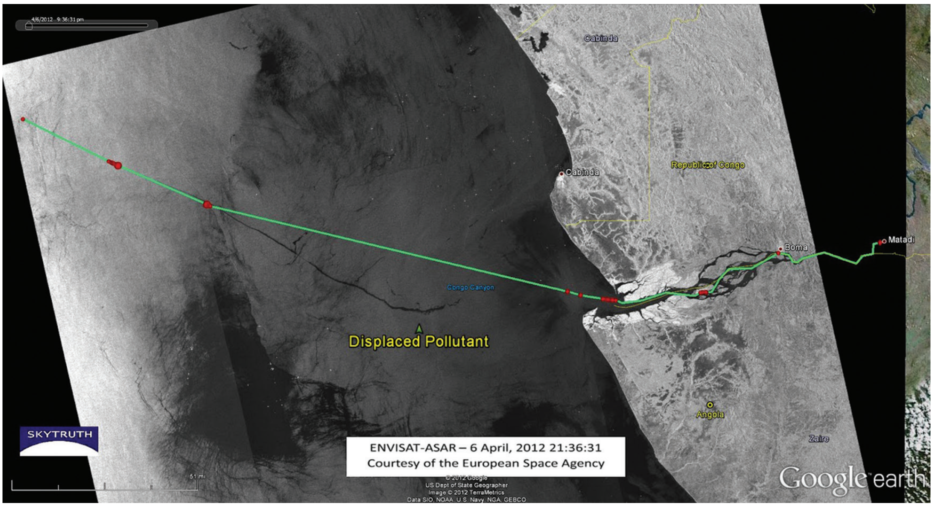

Figure 4. Work by SkyTruth to identify the Dona Liberta via AIS data (from SpaceQuest with locations depicted as red dots); a vessel causing an oily slick from a 92-mi long bilge dump off Congo and Angola in April 2012, which had been observed by Envisat Advanced Synthetic Aperture Radar images.

The Scientific Merit of AIS Data

While the above conservation applications of AIS data demonstrate the system's utility, scientific data should originate from transparent analytical processes leading to known, or estimates of a data's bias and uncertainty (Joly et al. 2010). Without such attributes, it may be unclear to researchers and managers how data are handled and errors addressed. Up until now, the limitations and biases of AIS data have been poorly articulated, if at all, when used in science applications (Table 4). Often, clearly articulated analytical approaches and discussions of data limitations are lacking, as is standardization in application of AIS data. This is a concern because even for small areas and short periods, data sets can include multiple vessels of different types collectively transmitting millions of messages with common errors in entries, while any number of vessels may not be included in the data set at all.

Use of AIS data in conservation applications has commonly entailed the use of parsed AIS data, culling undisclosed numbers of aberrant or unreadable records; resultant data sets are frequently used without consideration of effective coverage areas, availability of coverage, unrecorded but present vessels, or frequently use proprietary black-box algorithms to allocate specific attributes to a vessel or its behavior. While these broad issues may not be problematic if depicting a well-used vessel lane, they do become important as finer scale questions regarding policy-relevant topics are considered; including the impacts of specific vessel types, overall number of vessels in an area, vessel speeds, seasonality, and fine-scale movement patterns of the fleet as a whole (Fig. 1). Without such information and with a lack of standards or consistency between studies, results will be less meaningful, or of dubious validity for comparison across studies, regions, and time (Table 4).

Table 4. Bias and uncertainty associated with key Automatic Identification System (AIS) data variables of interest to the conservation community. IMO = International Maritime Organization; MMSI = Maritime Mobile Service Identity; SAR = Synthetic Aperture Radar.

Data of interest	Data component	Entry	Example of error	Bias	Work around?
[1] Data inherently missing	Raw data	n/a	Vessels not using their AIS.	Bias of omission due to an incomplete picture of vessel traffic for a specific area.	Document non-AIS local vessels using different sensors (e.g., radar). Remove inconsistently reporting vessels (e.g,. military) from analysis.
[2] Unreliable data	Raw data	n/a	Messages that fail their checksum (which are to be discarded by AIS devices) or other corrupted messages which are received but unreadable.	Corrupt or data loss may reflect non-random user input errors associated with a specific vessel type or origin, or errors of a particular receiver. Data loss may preclude using vessel transits as a metric for actual vessel numbers.	Reporting of data loss and established biases allows for correction factors.
			No data filtering/processing.	Greater reception near receivers; more data points in areas of slow (or anchored) vessel traffic can skew spatial density interpretations.	
[3] Vessel ID	MMSI	Initial install	Incorrect, outdated, or erroneous entry or erroneous default values. Occasionally a duplicate MMSI is reported.	Without a verifiable vessel ID, it may be impossible to track a vessel over time or associate a vessel with specific attributes (e.g., size or type).	IMO, MMSI numbers, and call sign can be verified from source registries.
	Vessel name, MMSI #, IMO #	Initial install	Incorrect, outdated, or erroneous entry. Duplicate vessel names are common (and permissible). Occasionally a duplicate MMSI is reported.	Without a verifiable vessel ID, it may be impossible to track a particular vessel over time or associate a particular vessel with specific attributes (e.g., size or type).	IMO, MMSI numbers, and call sign have specific attributes for verification.
[4] Vessel type	Ship type	Initial install	Undefined, missing, or non-specific.	Incomplete assessment of risks associated with specific vessel types.	Link with verified ship registry data to reported MMSI.
[5] Vessel dimensions	Length, beam, draft	Initial install	Incorrect or mis-located.	Inability to assess compliance or risk as it relates to bathymetry.	Use verified with ship registry data to reported MMSI.
	Static draft	User updated	Undefined, incorrect, outdated or reflects maximum draft.	Inability to assess compliance or risk as it relates to bathymetry.	Maximum draft may be verified with ship registry data.
[6] Speed over ground (SOG)	Knots	Automatic	Unavailable.	While some vessels can travel at very high speed (such as some new high speed ferries), data from AIS may include speeds in excess of 100 knots. These may be erroneous data or in some cases relate to SAR planes that also carry AIS.	Filter data based on reasonable vessel speeds (e.g., 2–35 kt) or check speeds using distance and elapsed time between two locations.
[7] Navigation status	15 codes	User updated	Outdated.	Wrong depiction of anchoring areas.	Cross-reference to vessel speed.
[8] Lat/long	Degrees	Automatic	Data on or over land.	Clustering, errant points.	Algorithms can be used to parse most erroneous points.
[9] Origin/destination	Port	User updated	Undefined, incorrect, or outdated.	Incomplete assessment of vessel traffic patterns in relation to specific routings.	Geospatial programming could be used.

Analysis of AIS Data Most Relevant to Conservation Applications

Recent reviews have helped demystify the complexities of large AIS data set decoding and offered clear direction to improving design of future applications (Calder and Schwehr 2009, Silber and Bettridge 2010, Shelmerdine 2015, Raymond and Schwehr 2015). Below we highlight a few analytical challenges and biases associated with the AIS data most relevant to conservation applications.

Relevance of AIS Data to the Overall Fleet—What is and What is not Included?

Data Inherently Missing from Analyses [1][1]

In assessing the linkages between maritime transport and conservation, a characterization of what AIS data provide (and do not provide) needs to be quantified wherever possible. Once an area of effective coverage has been delineated, the following factors can significantly affect the assessment of a specific area:

<u>Vessels not Carrying AIS systems</u>.—There is relatively little reporting of the numbers of vessels in an area that are not transmitting via AIS. Carson-Jackson (2012) discussed a 2009 Australian study that compared satellite AIS to the LRIT system, finding almost twice the number of vessels recorded by AIS (83% to 92% for AIS compared to 31% to 40% for LRIT), indicative of profound differences in gross use estimates based on different tracking systems. Barco et al. (2012) compared the number of vessels transmitting AIS signals to those detected using radar in the entrance to the Chesapeake Bay. They found that 49.7% of all vessels detected by radar were sending AIS signals; vessels not transmitting AIS consisted primarily of fishing, military, and law enforcement vessels (this area is not covered by a VTS, so AIS carriage was only required for foreign vessels transiting the region). Synthetic-aperture radar (SAR) satellite imagery and other tools are increasingly used to cross-reference and identify vessels not picked up by AIS. Both Erbe et al. (2012) and Merchant et al. (2014) discussed the issue of the potentially numerous, small vessels not equipped with AIS when assessing vessel noise impacts in an area.

<u>Limits to AIS Coverage</u>.—AIS transmissions to ground-based receivers are limited by "line of sight" in the few tens of miles, but topography can lead to areas with poor or no coverage at all (Shelmerdine 2015). Reception distance varies depending on the height of the receiving antenna and topography, but also on other dynamic factors such as meteorological conditions, atmospheric bounce, and interference from other radio signals (Silber and Bettridge 2010, Lapinski and Isenor 2011). While satellite reception offers larger coverage, reception is highly dependent on antenna placement and characteristics (e.g., omni vs directional, dipole, etc.), and the density of transmissions within its large reception footprint. AIS is designed for strong signals to override weak signals, thus ensuring vessels continuously receive the signals closest to them—those posing the highest collision risk. Satellites capture all signals, but are not always able to decipher/decode signals that are using the same transmission slot (slot collision). This "garbling" of data is a significant challenge for AIS reception, vessel detection, and data integrity. While almost 100% of vessels are received in low-density areas, this can drop significantly in high-vessel density areas (Høye et al. 2008, Last et al. 2014). This is further complicated by the lag in AIS reception (farther

1 Number in [brackets] refers to "Data of Interest" category in Table 4.

distance) and delayed data delivery via the satellite receiver (latency), or duration between points of data (revisits), which may not always be sufficient for tactical applications. Latency reported by exactEarth was 20–50 min, but can be as long as 90 min for one satellite and one ground station (Carson-Jackson 2012). This can only be reduced with additional satellites, multiple passes, and/or more ground stations.

Errors in a Variable that Preclude Import.—Most researchers utilizing AIS data report some level of data-loss due to unreadability. Last et al. (2014) report 0.25% of all their surface-received AIS messages from the North Sea were corrupt. MD Robards (unpubl data) found 8.2% of downloaded Satellite AIS data could not be parsed.

Deliberate Deactivation.—Recent research is demonstrating illegal activities coinciding with a vessel "going dark" (Windward 2014). While only a small proportion of overall vessel activity, these occurrences may be particularly pertinent to conservation (e.g., illegal fishing or dumping). However, the act of "going dark" itself is a detectable event (AIS mobile devices record the previous 10 power up-down sequences) and a potentially significant piece of data that may be generated by automated vessel behavior analysis.

Data Excluded Due to Unreliability [2]

While much of the AIS dynamic data (e.g., location, speed, course over ground) is accurate because it is automatically supplied by ship navigation systems or calculated by the AIS's internal GPS, the user-input attributes (i.e., length, draft, vessel type, cargo) are subject to input errors due to lack of proper training or diligence. Calder and Schwehr (2009) reported that 52% of the individual messages in a sample data set had to be rejected from their analysis of ship behavior due to concerns over message accuracy. Silber and Bettridge (2010) culled 28% (10,982 records) of a total 39,615 vessel transits. Harati-Mokhtari et al. (2007) reported up to 74% of user-input vessel type designations were unsatisfactory for subsequent analysis. Furthermore, default settings (that are applied, for example, after re-initialization of an AIS transmitter) on some AIS units can be problematic if not updated with new vessel or voyage information (Harati-Mokhtari et al. 2007, Schwehr and McGillivary 2007). These data considerations are significant; however, errors can be sometimes corrected during analysis using ancillary information from cross-referenced sources. Furthermore, in many cases, these errors pertain to specific fields that may not be critical to a specific analysis. This accuracy should improve as earlier AIS devices are replaced by newer versions that provide defined defaults and prohibit transmissions if the unit is encoded with obviously erroneous data (e.g., Maritime Mobile Service Identity or MMSI). New units also provide a dedicated window for the user to see what the AIS is transmitting, which is difficult to ascertain in earlier devices.

Some evidence points to illegal manipulation or misinformation being put into some AIS. While only a very small proportion of overall vessel activity, these occurrences may be particularly pertinent to conservation where hazardous materials are being carried (Windward 2014).

Primary AIS Variables of Interest for Conservation Applications

Static Data

Vessel's Identity [3].—AIS signals emanate from a "station" (radio) and not a vessel, so for most analyses of vessel traffic, a vessel identifier is needed. AIS data contain three forms of unique official identity: Maritime Mobile Service Identity (ITU assigned MMSI—unique nine-digit code common to all digital radios on board); the call-sign (also ITU assigned), which is only changed when the vessel changes flag; and the IMO number (permanently welded to the vessel hull). While vessel names are not necessarily unique, algorithms cross-referencing them with any one (or more) of these three unique identifiers lend to assured authentication of a vessel's identity.

Relatively low error rates are found with MMSIs of IMO vessels, with only 2% of MMSIs entered with the wrong number of digits in the Harati-Mokhtari et al. (2007) study. Silber and Bettridge (2010) reported low numbers of duplicate MMSIs and the use of a geo-feasibility test to assess this, given whether a vessel could travel from point to point within a reasonable time using a reasonable speed. Although United States Coast Guard (USCG) summaries suggest higher levels or unofficial MMSIs are in use in the United States, this has been mitigated by the Federal Communications Commission (FCC) now issuing an MMSI with every radio license it issues (previously a licensee would have to pay US$150 to obtain their own MMSI) and that new AIS devices will not operate with obviously incorrect MMSIs (International Electrotechnical Commission 2012, Winkler 2012a). MMSIs (of seagoing vessels), call signs, and IMO numbers are catalogued in station and ship registry databases[2] and consequently allow for cross-referencing databases.

<u>Vessel Type</u> [4].—Operators code vessel types under titles of "cargo," "tanker," and "passenger," etc., as defined in the ITU 1371-5. However, the cargo vessel category is broad and might encompass any ship that carries a range of goods and materials from one port to another, including container ships, bulk carriers, and general cargo ships. The tanker category generally designates ships carrying oil or other liquid chemical products. Passenger vessels include large cruise ships, as well as smaller (often coastal) passenger ferries. Conversely, some cargo ships can have relatively significant passenger capacities (over 100 births) and if carrying more than 12 passengers are classed under SOLAS as passenger ships, not cargo ships. Shelmerdine (2015) also highlight that fishers do not always categorize their vessels as fishing; rather, categorizing their vessels as "other" (a similar problem was noted for offshore oil related vessels such as supply or anchor handlers). Like for many other attributes, linking MMSI numbers to external ship registry databases can provide more detailed vessel information and opportunities for quality control.

Clearly the hazardous nature of some cargos is of interest to conservationists, particularly as it relates to potential spills. However, given the sensitivity of the data, very few vessels actually report this cargo (for example, two-thirds of vessels did not report cargo in the Aleutian Islands in the United States; NRPG, 2015). The United States Coast Guard actually recommends that this field not be used in the United States (see USCG Automatic Identfication System U.S. Encoding Guide available at http://www.navcen.uscg.gov/pdf/AIS/USCG_AIS_Encoding_Guide_150708.pdf).

<u>Vessel's Dimensions</u> [5].—Vessel dimension (length and beam) are derived from the positioning system antenna location (reference point for reported vessel position) (International Telecommunication Union—Radiocommunication Sector 2014). While this is unique to a particular vessel, its length and beam are not. However,

2 ITU database is the primary source as they issue MMSIs. Other sources include USCG Information Exchange; Federal Communication Commission's Universal Licensing System; Vessel Tracker; Digital Seas; IHS Vessel Registry.

misidentifying this position can have consequences on how a vessel is portrayed, which is often relevant to particular policy requirements. In a study of vessel operation relative to a North Atlantic right whale conservation measures (affecting vessels of a certain size), Silber and Bettridge (2010) found erroneous data most frequently included low values (<6 m length), with overall, inaccurately entered vessel length occurring in 1007 of 6371 (or 16%) entries in their January 2009 data, representing 103 different vessels. Reconstituting accurate information required online databases cross-linked to vessel identification.

Instantaneous and Dynamic Data

Speed Over Ground [6].—Vessel speed over ground (SOG) is important from a conservation perspective due to the relation with speed restrictions (and often as they relate to vessel strikes on large cetaceans). It may also be an important safety of navigation factor in certain times or locations in which maximum or minimum speeds may need to be maintained to avoid hazards. However, while this data field can be useful, many researchers calculate average speed between successive points of data based on change in position and time.

Navigation Status [7].—Navigational status can provide information on such things as anchoring, fishing, and when a vessel is not under command; however, status is infrequently updated properly. Nevertheless, it can be verified, or where missing, inferred to some degree by cross-referencing with vessel speed, where a 2-kt threshold is often used to distinguish between vessels at anchor, moored, or stationary, with those underway.

Location [8].—Information is provided automatically via GNSS. Ng et al. (2013) noted removing points on land as obvious data errors, but did not indicate if any points were erroneous on water as well. Silber and Bettridge (2010) and Willems et al. (2009) both established criteria to assess the reasonableness of subsequent vessel locations based on necessary vessel speeds between points. Sources of location error can include (in order of importance): (1) the switching on or off of the GPS or other similar navigational system feeding position data to a vessel's AIS equipment; (2) poor or incorrect data input into a vessel's AIS equipment (e.g., antenna offset); (3) use of the same MMSI by two or more vessels; and (4) deliberate spoofing or misinformation (D Lorenzini, unpubl data).

Trip Data

Origin/Destination [9].—The AIS Destination and Origin parameters can be of great value in assessing traffic patterns and modeling vessel traffic between ports, which is valuable in understanding and predicting future flows of vessels along specific routes. However, while a required field and format per the IMO guidelines, this manually entered information is not well used or enforced, and frequently contains operator errors or carry-over entries from past voyages. Harati-Mokhtari et al. (2007) reported a 49% error rate for the fields of destination and estimated time of arrival. Bailey et al. (2008) and Shelmerdine (2015) similarly found the destination field to contain the most errors of all AIS input fields. These data may become confounded if multiple ports or waypoints are involved in a particular trip.

Issues with Pre-processed Data

Due to the complexities of data handling, there is increasing use of post-processed AIS data products, frequently associated with proprietary algorithms and data sampling rates developed and held by private AIS data providers. Without transparency or metadata, there is little way to tell if algorithms contain assumptions or flaws that may be inappropriate for a specific analysis. Users should be cautious as to what assumptions these algorithms make, and that some proprietary products use only a small component of the AIS data. The general portrayal of vessel routings in conservation applications may also belie underlying traffic volumes and seasonality, which are both critical to understanding risk and impacts.

Issues with Interpolating Densities from Raw AIS Data

Data can: (1) over-represent vessel traffic volume (particularly for ground-based receivers) where more messages are obtained from vessels in close proximity to the receiver than from distant vessels; (2) under-represent vessel traffic volume (particularly for ground-based receivers) where vessels are not being detected due to topography; or (3) over-represent vessel traffic volume where slow (or anchored) vessels in a particular area are not reflected in the use of vessel instances, rather than the use of cumulative vessel position points for a particular area.

New efforts are striving to improve the interpolation and visualization of AIS data. For example, Willems et al. (2009) produced data visualizations based on density fields (Fig. 2). Whereas large kernels are used to show an overview of vessel lanes, vessel speed variation of individual vessels are shown with a small kernel, highlighting anchoring zones where multiple vessels stop.

Recommendations to Increase the Value of AIS Data

The number of vessels carrying AIS and the range of transmitting capabilities is expanding. Given that AIS already provides precautionary, planning, and management benefits for conservation, opportunities will continue to develop for better achieving the full conservation potential of AIS.

Broad recommendations for improving the functionality of AIS for Maritime Domain Awareness are addressed in detail elsewhere (e.g., Carson-Jackson 2012, IALA 2012, Shelmerdine 2015, Raymond and Schwehr 2015). Here, we focus on specific recommendations for improving existing applications in marine resource conservation.

Improving Coverage and Reliability of AIS Data

Training.—Mariner's Watch Standing Guidelines could add more information about AIS.

Enforcement.—Flag states (those with the authority to enforce correct AIS configuration) could automatically cross-reference AIS data using authoritative information sources, and could require correction of obviously erroneous or non-standard data format (e.g., non-valid MMSI number, or origin/destination port identifier that don't comply with standardized recommendations (IMO 2004, and Automatic Identification System U.S. Encoding Guide at http://www.navcen.uscg.gov/pdf/AIS/USCG_AIS_Encoding_Guide_150708.pdf). Consistent default values for all fields would also help identify where no data have been entered. Calls have previously been made for enforcement or monitoring programs in the United States, administered by the US Coast Guard that could correct over 95% of known programming errors or miscommunications (Winkler 2012b).

AIS Expansion.—Individual flag states or insurers could require AIS on smaller classes of vessels and additional ground based receivers could be installed in locations of conservation interest where there are gaps in receiver coverage, or too much traffic for space-based receivers to be effective.

Improvement to Message Formats.—AIS developers could add a communication state to position reports of all AIS transmissions (already included in AIS Class A position reports), which, along with the time stamp, can provide information on the existence of radio interference or other anomalies affecting reception of GPS or AIS signals. Working with these data would help establish areas where vessels are transiting, but are not appearing in AIS.

Improvements to AIS Receiver Technology.—Satellite AIS providers could be encouraged to use the latest protocols for the enhanced reception of long range AIS broadcasts (International Telecommunication Union—Radiocommunication Sector 2014) and improve the ability to track lower powered AIS Class B AIS transmission. Maximizing the value of the Class B AIS system would augment stipulating greater use of Class A AIS, such as on fishing boats as in the European Union.

Improve Access, Consistency, and Usability of Data to a Wider Suite of Users

Access.—Flag states could provide a clearinghouse of AIS data for research that includes key metadata about processing of the variables discussed above. This would allow the research community to better provide the analyses necessary to inform marine conservation applications; this has been the practice for NOAA's Right Whale Protection Areas (Silber and Bettridge 2010). Schwehr (2011) has also proposed automated data warehousing and data analysis for specific areas. With future improvements to AIS coverage, large areas can be covered in such pre-filtering archival efforts (initial efforts in the United States are processed by USCG and available at http://marinecadastre.gov/ais/). Clearly this could be scaled globally, using a centralized archive for access for key aspects of the AIS data (both terrestrial and satellite), but will likely require agreements with, and funding for, private satellite providers to make pre-filtered data more available.

Consistency.—Journals could encourage standardizing analytical approaches and metadata reporting of AIS data, particularly pertaining to bias factors listed in Table 4 (including data-loss, filtering, and algorithms). This would improve comparability of analyses across regions and time.

Usability.—Provision of data by AIS providers that has been pre-processed as unique vessel transits, rather than individual points, would vastly simplify most analyses and alleviates distribution of raw point data by AIS providers. Shared protocols for such transit data should be developed that include sampling rates and beginning/end points.

Improvements and Expanded Uses of the AIS

- Development of additional algorithms for anomaly detection of unusual, suspicious, or malicious behavior, such as spoofing would support management and enforcement agencies. Researchers and providers could automate the detection of signal loss from vessels on the high seas, which can be indicative of illegal fishing, lack of use of authorized ballast water exchange areas, adherence to speed restrictions, or non-compliant vessel behavior in Particularly Sensitive Sea Areas.

- New protocols with broader VHF Digital Exchange could supersede what is currently possible with AIS (e.g., VHF Data Exchange). These would require increased bandwidth and the design and adoption of new messages. For example, adding forward error correction, cryptographic signatures, and an improved message definition language.
- Changes to the protocols for satellite AIS that reduce the volume of data would improve detection probabilities (e.g., Høye et al. 2008). In some cases, this will require new capabilities for AIS satellite services or new types of AIS infrastructure.
- Relaying of ship-to-ship, ship-to-shore and shore-to-ship messaging (such as weather, environmental risks) as part of an overall e-Navigation strategy would add value to the current AIS system (Tetreault et al. 2010; IMO SN1/Circ.289), but will require software updates and new user requirements. New efforts by European countries (MonaLisa Project) and the Baltic States (EfficienSea Project) are moving in this direction, and could inform development of valuable components of the IMO's Polar Code voyage planning requirements.

Conclusions

AIS is a valuable tool for improving navigation safety and transportation efficiency, as well as for informing conservation planning and monitoring. However, care needs to be taken, both in data processing, and particularly with respect to better understanding the mechanisms of impacts between vessel traffic, the marine environment, and the wildlife that live in it—overlap in space and time alone is not confirmation of some real or potential environmental impact.

The role and utility of AIS in marine conservation contexts could be greatly enhanced by a number of changes in the ways that messages are transmitted, processed, and made available to all users. Standardizing data processing or filtering methodologies and making these readily available through a single (realistically national, but ideally international) repository, would provide cost-savings in analysis, and foster collaboration among various organizations. Such an effort is beyond the scope of this review, but is ripe for consideration in a practitioner's workshop environment. So to is consideration of providing open-source versions of proprietary software. National organizations, such as the coast guards and marine transportation administrations, are frequently the repository of national AIS data and should work to adopt an archival standard(s) and work with data providers to make AIS data more available through software such as AISMiner (used by the United States Coast Guard). A more economical and efficient network of AIS users and analysts may ultimately result in greater engagement by vessel companies and operators in the conservation of marine resources.

Acknowledgments

Douglas Burn and Aaron Poe of the Aleutian and Bering Sea Islands (ABSI) Landscape Conservation Cooperative (LCC) provided comments on earlier drafts. Partial funding for MDR was provided by ABSI LCC, Oak Foundation, and Pew Charitable Trusts.

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