Maritime Surveillance with Small Satellites

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Abstrakt

Die Überwachung des Seeverkehrs ist heutzutage eines der interessanten Themen. Die Überwachung des Ozeans und der ausschließlichen Wirtschaftszone (AWZ) ist für viele Länder eine weit verbreitete Aufgabe. Eine der entscheidenden Aufgaben ist die Überwachung des Schiffsverkehrs und seiner Aktivitäten im Meer. Die Seeüberwachung verwendet normalerweise ein kooperatives und ein unkooperatives Überwachungssystem. Das automatische Identifikationssystem (AIS) ist ein notwendiges Instrument, das von der Internationalen Seeschifffahrtsorganisation (IMO) reguliert wird und von verschiedenen Schiffsarten für die Sicherheit des Seeverkehrs implementiert werden sollte. Die Überwachung des AIS vom Satelliten aus schließt die Lücke zwischen AIS, die an der Küste und auf offener See betrieben werden.Die Überwachung mit Satelliten hat jedoch auch eine Einschränkung, da AIS als kooperatives Überwachungssystem bei illegalen Aktivitäten im Ozean absichtlich abgeschaltet wird. Daher ist das unkooperative Überwachungssystem, z. B. Radar oder Bild vom Satelliten, notwendig. Die Hauptmotivation der Forschung besteht darin, zu untersuchen, wie ein kleiner Satellit wie LAPAN-A2 und LAPAN-A3, der einen AIS-Empfänger und seine optische Kamera trägt, an der Überwachung des Seeverkehrs beteiligt sind.Diese Satelliten sind die ersten kleinen Satelliten, die 2015 bzw. 2016 gestartet wurden und neben anderen Nutzlasten im äquatorialen und polaren Orbit auch AIS und optische Kamera an Bord haben. In dieser Arbeit wurden die AIS-Leistungen dieser Satelliten untersucht und eine Wahrscheinlichkeitserkennung aufgrund der AIS-Signalkollision oder anderer globaler Interferenzen erstellt. Diese Arbeit beschreibt eine Lösung zur Verwaltung des ungültigen AIS-Datenempfangs durch den Satelliten. Die AIS-Empfangsleistung wurde auch untersucht, indem verschiedene Ausrichtungen der integrierten AIS-Antenne vorgenommen wurden, um ein besseres Verständnis des AIS-Signalempfangs durch den Satelliten im Orbit zu erhalten. In dieser Arbeit werden auch einige wichtige maritime Fälle beschrieben, die von diesen Satelliten im indonesischen Ozean entdeckt wurden, einschließlich typischer Spoofing und potenziell illegaler Aktivitäten im Ozean. Die Bilder dieser Satelliten zwischen digitalen hochauflösenden und mittelauflösenden Multispektralkameras wurden ebenfalls untersucht, um das Bild des Schiffes zu erhalten. Die Bedeutung der gleichzeitigen Fusion von Satellitenbild- und AIS-Daten als kooperatives und unkooperatives Überwachungssystem nahezu in Echtzeit durch jeden LAPAN-A2- und LAPAN-A3-Satelliten wurde ebenfalls erörtert. Schließlich können die aus LAPAN-A2 und LAPAN-A3 gewonnenen Verbesserungen für das LAPAN-A4-Satellitendesign verwendet werden, dem Nachfolger beider Satelliten, die auch Multispektral- und AIS-Empfänger tragen. Und es ist auch wertvoll beim Entwurf einer Implementierung für einen zukünftigen Konstellationssatelliten in einer äquatorialen Umlaufbahn.

Abstract

Maritime surveillance is one of the interesting topics nowadays. Monitoring of the ocean and the exclusive economic zone are a prevalent task for many countries. One of the crucial tasks is to make surveillance of the ship traffic and their activities in the ocean. Maritime surveillance usually uses a cooperative and non-cooperative surveillance system. The Automatic Identification System (AIS) is a necessary tool regulated by the International Maritime Organization (IMO) that should be implemented by several types of ships for maritime safety. Monitoring AIS from the satellite close the gap between AIS that operate in coastal and open seas. However, the surveillance with satellite also has a limitation since AIS as a cooperative surveillance system tends to be switched off intentionally during illegal activities in the ocean. Hence the non-cooperative surveillance system, i.e., radar or image from the satellite, is necessary. The primary research motivation is to examine how a small satellite like LAPAN-A2 and LAPAN-A3 that carries an AIS receiver and its optical camera involving in maritime surveillance. Those satellites are the first small satellite launched in 2015 and 2016, respectively, that carry AIS and optical camera onboard besides other payloads in equatorial and polar orbit. This work examined AIS performances from those satellites and creating probability detection due to the AIS signal collision or other interference globally. This work describes a solution to manage invalid AIS data received by satellite. AIS reception performance was also investigated by making several orientations of the onboard AIS antenna to get a better understanding of the AIS signal reception by the satellite in orbit. Several important maritime cases detected by those satellites in the Indonesian ocean, including typical spoofing and potentially illegal activity in the ocean, also describe in this work. The images from those satellites between digital high resolution and medium resolution multispectral cameras were also examined to get the image of the ship. The importance of the fusion of satellite image and AIS data simultaneously as a cooperative and non-cooperative surveillance system in near real-time by each LAPAN-A2 and LAPAN-A3 satellites, also discussed. Finally, further improvement learned from LAPAN-A2 and LAPAN-A3 can be used for LAPAN-A4 Satellite design, the successor of both satellites that also carry multispectral and AIS receiver. And it also valuable in designing implementation for future constellation satellites in an equatorial orbit.

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List of Abbreviations

ACS	Attitude Control System
AIS	Automatic Identification System
ADS-B	Automatic Dependent Surveillance-Broadcast
APRS	Automatic Packet Reporting System
ASM	Application-Specific Messages
CCD	Charge-Coupled Device
CCSDS	The Consultative Committee for Space Data Systems
COTS	Commercial off-the-shelf
COG	Course over Ground
CRC	Cyclic Redundancy Check; an error-detecting code
CSTDMA	Carrier Sense Time Division Multiple Access
DLR	German Aerospace Center
ESA	European Space Agency
ETA	Estimated Time Arrival
FOV	Field of View
FPGA	Field-Programmable Gate Array
FSI	Frequency Offset Indicator
GEO	Geosynchronous Equatorial Orbit
GMDSS	Global Maritime Distress Safety System
GT	Gross Tonnage; the molded volume of all enclosed spaces of the ship
HDTV	High Definition Television, a substantially higher resolution of a video camera
IALA	The International Association of Marine Aids to Navigation and Lighthouse Authorities
IoT	Internet of Things
ISRO	Indian Space Research Organization
ITU	International Telecommunication Union
IMO	International Maritime Organization
KML	Keyhole Markup Language, a file format used to display geographic data and visualization within internet-based
LAPAN	Indonesian Institute of Aeronautics and Space
LEO	Low Earth Orbit, an altitude between 200 and 2000 km
LEOP	Launch and Early Orbit Phase
LISA	Line Scan Imager
LRIT	Long Range Identification and Tracking
MMSI	Maritime Mobile Service Identity

M2M	Machine to Machine Communication
MSC	Maritime Safety Committee
NIR	Near Infra Red
NMEA	National Marine Electronics Association
OBDH	On-Board Data Handling
PCDH	Power Control and Data Handling, integration between Power Control Unit and On-Board Data Handling
RAIM	Receiver Autonomous Integrity Monitoring
RSSI	Received Signal Strength Indicator
RGB	Red Green Blue channel/spectrum
SAR	Search and Rescue/Synthetic Aperture Radar
SDR	Sofware Defined Radio
SOTDMA	Self-Organized Time Division Multiple Access
SOLAS	International Convention for the Safety of Life at Sea
SOG	Speed over Ground
TLE	Two Line Element
UHF	Ultra-High Frequency
UTC	Coordinated Universal Time
VDES	VHF Data Exchange
VDL	VHF Data Link
VHF	Very High Frequency
VTS	Vessel Traffic Service; a marine traffic monitoring system established by the harbor or port authorities, similar to air traffic control for aircraft

1

Introduction

1.1 Overview of Maritime Surveillance

Monitoring of activities at sea and optimizing maritime situational awareness (MSA) are topics of substantial and rising consideration. The synergy integration of data from land-based, sea-based, aerial, and spaceborne sensors with information from geographic information systems (GIS) and vessel information repositories contributes to a better understanding of the situation.

The International Maritime Organization (IMO) revised Chapter V of the Safety of Life at Sea Convention (SOLAS) in 2000. A transponder and communication protocol called an automatic identification system, or AIS, became compulsory for most of the commercial shipping fleet by the end of December 2004 to reduce the risks of collision and grounding accidents [1].

From the beginning of the 2000s, several publications about the AIS system are oriented towards navigational safety and the risk of collision. Afterward, authorities and research centers focused on such a device's potential to improve navigation safety and security through ship tracking. Since the ship-to-ship signal is usually limited to 20 nautical miles, and the shore-to-ship signal is limited to 40-50 nautical miles, the military and maritime space researchers, especially in Europe, as well as industry, are developing a satellite-based observation method to expand the geographic range over which ships can be identified. The promising feasibility studies about satellite-based AIS capabilities and promising a long-range tracking capability of the world fleet published concurrently [41].

Maritime tracking with AIS makes the system accessible for Maritime Domain Awareness by validating data, correlation, data fusion, and functionally storing AIS data for future study. Vessel detection has a wide range of applications, including maritime safety, marine traffic, marine pollution, marine spatial planning, fisheries management, illegal fishing, defense and maritime security, maritime piracy, irregular migration, and border control.

Surveillance of the maritime typically divides into a cooperative system and a non-cooperative surveillance system. The cooperative system implies that the vessel is reporting with any means of transmission regulated by law such as AIS, VMS (Vessel Monitoring System), radio communication. In contrast, the non-cooperative surveillance system is a surveillance system that does not require any contact with the vessel. The cooperative system, such as AIS having some transmission issues due to the system's saturation in locations with high vessel density, weak quality transmissions due to equipment on the vessel or receiver, and disabling of AIS transmitters in purpose.

For (non-cooperative) observation systems, the primary maritime surveillance sensors are optical cameras, infrared cameras, and radar, apart from visual spotting. These can be deployed from land, boats, aircraft, or satellite. A type of sensor and each device has its strengths and disadvantages related to features such as spatial resolution, update rate, range, coverage, durability, latency, and cost. Satellite-based sensors have the specific advantages of remote access, global reach, regular update, and significant data collection volume. In some scenarios, they are the only feasible option and, in others, the most economical one. Notably, there is a growing need for earth observation by using small and cost-effective satellite missions. Small satellite missions can be carried out reasonably inexpensive, utilizing commercial off-the-shelf technology or improved by using advanced technologies [2]. Therefore, the usage of satellite images is an essential tool also to find vessels on the sea. In particular, satellite-based radar images, usually as Synthetic Aperture Radar (SAR), has become famous for maritime surveillance: ships are detected relatively easily and independently of the presence of clouds or daylight. However, due to the expensive payload, complex processing and also operation efficiency becomes a drawback.

On the other hand, the interest in optical image's potential for maritime surveillance has dramatically increased recently, maybe in the first place due to the increase in optical imaging satellites also from small satellite missions. Optical satellites and the number of publications on ship detection in optical images have grown exponentially during the last decade [3]. The growth of optical image satellites is also supported by recent development that brings the cost to develop the small satellite that could carry optical payload affordable.

1.2 Thesis Objectives

This thesis aims to examine several aspects of small satellite capabilities in serving maritime surveillance. The focus of this examination is focusing on how small satellites of LAPAN-A2 and LAPAN-A3 serving maritime surveillance with its AIS receiver and optical images. Using those satellites becomes interesting since those satellites orbiting in the different orbit and carrying a different optical payload designed for land cover and ocean monitoring. This study includes AIS reception performance and experience gained from both satellites. The simultaneous combination of AIS and an optical image from each satellite was also examined.

Several chapters are divided to fulfill the objective of the thesis. The first chapter introduces the background while the second chapter describes AIS's history, regulation, the functionality of AIS in the maritime domain, and the significant role of space-based AIS compared with terrestrial or coastal AIS. The third chapter describes LAPAN satellite's role in maritime surveillance, describing LAPAN-A2 and LAPAN-A3 satellite systems & its AIS reception performance globally. This chapter also describes several maritime cases and potentially illegal activity in the ocean detected during the satellite's operation.

The fourth chapter describes the problem of space-based AIS in certain areas, while the fifth chapter describes several solutions to solve the problem. The sixth chapter deal with optical ship observation through the satellite. This chapter shows image results from LAPAN-TUBSAT/LAPAN-A1, LAPAN-A2/LAPAN-ORARI, and LAPAN-A3/LAPAN-IPB satellites for vessel observation. Since each of LAPAN-A2 and LAPAN-A3 satellites has AIS and imager payload, the simultaneous combination between high-resolution image or medium resolution image with AIS information is demonstrated and investigated in this section. Summary and recommendation of the thesis described in chapter seven. This chapter also describes the resulting study's implementation outlook for the future small satellite, including the next LAPAN's satellite program.

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2

Overview of Automatic Identification System (AIS)

2.1 Description of The Standard AIS Between Ships to Avoid A Collision

In 2000, IMO adopted a new requirement for all ships to carry automatic identification systems (AIS) that capable of providing information about the ship to other ships and coastal authorities automatically. According to IMO (International Maritime Organization), there is a carriage requirement for shipborne navigational systems and equipment that sets out navigational equipment to be carried on board ships. This requirement, according to ship type, as stated in Regulation 19 of SOLAS Chapter V [1].

The regulation requires AIS to be fitted aboard all ships of 300 gross tonnages and upwards engaged on international voyages, cargo ships of 500 gross tonnages and upwards not engaged on international voyages, and all passenger ships irrespective of size. As of 31 December 2004, the provision became effective for all vessels.

Those ships fitted with AIS shall maintain AIS in operation at all times except where international agreements, rules, or standards provide for the protection of navigational information. A flag state can exclude vessels from carrying AIS if the vessels have been permanently taken out of operation within two years of the date of implementation. Standard performance for AIS was adopted in 1998.

The regulation requires that AIS shall [4]:

- Provide information - including the ship's identity, type, position, course, speed, navigational status, and other safety-related information - automatically to appropriately equipped shore stations, other ships, and aircraft;
- Receive automatically such information from similarly fitted ships; · monitor and track ships;
- Exchange data with shore-based facilities.

IMO also releases Recommendation on Performance Standards for Universal Automatic Identification System (AIS) that AIS should be capable of [5]:

1. Providing information automatically and continuously to a competent authority and other ships, without the involvement of the ship's personnel;
2. Receiving and processing information from other sources, including that from a competent authority and other ships;
3. Responding to high priority and safety-related calls with a minimum of delay, and
4. Providing positional and maneuvering information at a data rate adequate to facilitate accurate tracking by a competent authority and other ships.

The policy applies to ships built on or after 1 July 2002 and ships engaged in international voyages built before 1 July 2002, as stated in the following schedule:

- Passenger ships, not later than 1 July 2003;
- Tankers, not later than the first survey for safety equipment on or after 1 July 2003;
- Ships, other than passenger ships and tankers, of 50,000 gross tonnages and upwards, not later than 1 July 2004 [1].

An amendment adopted by the Diplomatic Conference on Maritime Security in December 2002 states that, additionally, ships of 300 gross tonnages and upwards, but less than 50,000 gross tonnages, are required to fit AIS not later than the first safety equipment survey after 1 July 2004 or by 31 December 2004, whichever occurs earlier in which the original regulation adopted in 2000 exempted these types of vessels [6].

According to the 79th session in December 2004, the Maritime Safety Committee (MSC) approved that, concerning the issue of freely available automatic information system (AIS)-generated ship data on the world-wide-web, the publication on the world-wide-web or elsewhere of AIS data transmitted by ships could be detrimental to the safety and security of ships and port facilities and was undermining the efforts of the Organization and its Member States to enhance the safety of navigation and security in the international maritime transport sector [7].

The Committee condemned the regrettable publication on the world-wide-web, or elsewhere, of AIS data transmitted by ships and urged Member Governments, subject to the provisions of their national laws, to discourage those who make available AIS data to others for publication on the world-wide-web, or elsewhere from doing so. The Committee also condemned those who irresponsibly publish AIS data transmitted by ships on the world-wide-web, or elsewhere, mainly if they offer services to the shipping and port industries [4][7].

Compared to the radar system, AIS provides more details of the information. The information provided by the AIS should include [5]:

Table 2.1 AIS Information Content

Static	Dynamic	Voyage Related
• IMO number (where available) • Call sign & name • Length and beam • Type of ship • Location of the position-fixing antenna on the ship (aft of the bow and port or starboard of centerline)	• Ship's position with accuracy indication and integrity status • Time in UTC * • Course overground • Speed over Ground • Heading • Navigational status (e.g., at anchor, manual input) • The rate of turn (where available) • Optional - Angle of the heel (where available) ** • Optional Pitch and roll (where available) **	• Ship's draught Hazardous cargo (type) *** • Destination and ETA (at master's discretion) Optional - Route plan (waypoints) *

* Date to be established by receiving equipment.

** field has not provided in the basic message

*** As required by the competent authority

Besides the information in Table 2.1, the AIS message also provides Short safety-related messages.

That above information is then separated into 27 messages types that AIS can transmit, and each message has a specific purpose. This information can be transformed into useful information for maritime traffic analysis, e.g., vessel path prediction and collision avoidance. AIS uses a transmission protocol called a Self-Organized Time Division Multiple Access (SOTDMA). This protocol allows AIS to be an autonomous actor in the vessels and ensure reliable ship-to-ship communications.

AIS designed for operation in the VHF maritime mobile band, with 25 kHz bandwidth. The minimum requirement for certain types of equipment may be a subset of the VHF maritime band. Four frequencies have been designated for AIS use worldwide, on the high seas, and in all other areas, unless other frequencies are designated on a regional basis for AIS purposes. The four designated frequencies are [8]:

- AIS 1 (Channel 87B, 161.975 MHz) (2087)5;
- AIS 2 (Channel 88B, 162.025 MHz) (2088)1;
- channel 75 (156.775 MHz) (1075), Message 27 transmission only (long-range AIS); and
- channel 76 (156.825 MHz) (1076), Message 27 transmission only (long-range AIS).

AIS transceivers automatically broadcast information, such as their position, speed, and navigational status, at regular intervals via a VHF transmitter built into the transceiver. The data originates from the ship's navigational sensors, typically its global navigation satellite system (GNSS) receiver and gyrocompass. Other information, such as the vessel name and VHF call sign, is programmed when installing the equipment and regularly transmitted. The signals are received by AIS transceivers fitted on other ships or land-based systems, such as VTS systems. The vessel's collected information can be displayed on a screen or chart plotter, showing the other vessels' positions in much the same manner as a radar display. Data is transmitted via a tracking system that makes use of SOTDMA datalink.

While static and voyage-related data of the ship are sent every 6 min or on request, interval reporting of AIS message defined based on the dynamic status shows in the table below:

Table 2.2 Shipborne Reporting Interval [8]

Ship's dynamic conditions	**Nominal reporting interval**
Ship at anchor or moored and not moving faster than 3 knots	3 min
Ship at anchor or moored and moving faster than 3 knots	10 s
Ship 0-14 knots	10 s
Ship 0-14 knots and changing course	3 1/3 s
Ship 14-23 knots	6 s
Ship 14-23 knots and changing course	2 s
Ship > 23 knots	2 s
Ship > 23 knots and changing course	2 s

AIS signals are broadly classified as 'Class A' and 'Class B,' where AIS-A is carried by international voyaging ships with gross tonnage (GT) of 300 or more tones, and all passenger ships regardless of size. In 2006, International Electrotechnical Commission (IEC), through document number 62287-1, published the Class B type AIS transceiver standard specification designed to enable a modest and lower-cost AIS device. Low-cost Class B transceivers then became available in the same year. This triggering mandate adoptions by numerous countries and making large-scale installation of AIS devices on vessels of all sizes commercially viable, the fishing sector, and recreational vessel users.

2.1.1 Class A

The Vessel-mounted AIS transceiver (transmit and receive) unit operates using SOTDMA, as in Figure 2.1. Intended for large commercial & passenger vessels, it requires a transceiver to maintain a regularly updated slot map in its memory such that it has prior knowledge of slots that are available for it to transmit every 2-10 seconds interval while underway and 3 minutes while at anchor. Also, the ship with class A could transmit additional information every 6 minutes. According to IMO, standard performance on the required ship reporting capacity is a minimum of 2,000-time slots per minute, even though it provides 4,500-time slots per minute. Hence, the SOTDMA broadcast mode allows the system to be overloaded by 400 to 500% by sharing slots. Still, it provides nearly 100% throughput for ships closer than 8 to 10 nm to each other in a ship to ship mode. Drop-out of the message happens to the farther ship in case of system congestion, to give preference to near targets, which are of more significant concern to shipping operators. In reality, the system's capacity is almost unlimited, allowing a significant number of ships messages to be accommodated simultaneously. SOTDMA transceivers then pre-announce their transmission, effectively reserving their transmit slot. Based on the reliability, SOTDMA transmissions are prioritized within the AIS system by using two receivers in continuous operation [9]. Class A's must have an integrated display, transmit at 12.5 W, interface capability with multiple ship systems, and offer a sophisticated selection of features and functions. AIS technology allows the display of information previously only available to modern Vessel Traffic Service (VTS) centers. It provides much clearer information allowing mariners to more accurately identify and contact any vessel within the VHF range. In 2010 most commercial vessels operating on the European inland waterways were required to fit an Inland waterway certified Class A and all EU fishing boats over 15m to have a Class A by May 2014 [10].

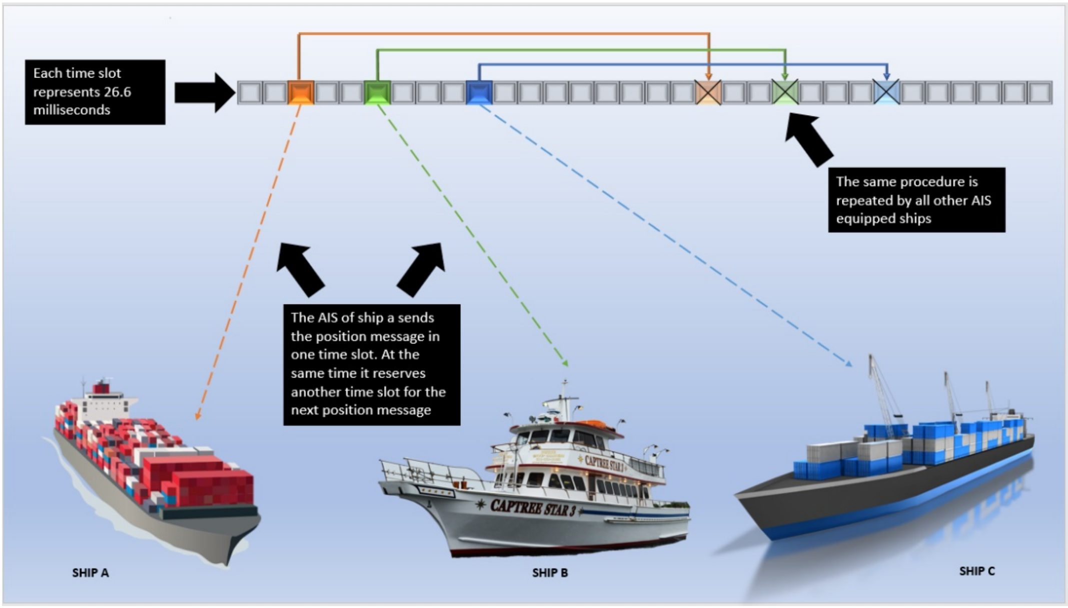

Figure 2.1 AIS transmission. (Adapted from [9])

2.1.2 *Class B*

Aimed at smaller commercial and leisure ship markets as typically non-regulated; however, it recently starts to be regulated in several countries. Ship-mounted AIS transceiver (transmit and receive) operates using either carrier-sense time-division-multiple-access (CSTDMA) or SOTDMA. CSTDMA protocol, which politely interweaves with Class A transmissions. CSTDMA transceivers listen to the slot map shortly before transmitting, then look for a slot where the 'noise' in the slot is the same or close to background noise, meaning that another AIS device is not using the slot. Class B transmit at 2 W and are not required to have an integrated display. Class B can be connected to most display systems where the received messages are displayed in lists or overlaid on charts. The default transmits rate of AIS usually every 30 seconds, 3 minutes while anchor, but this can be varied according to vessel speed or instructions from base stations and also can transmit supplemental data at 6 Minutes interval. The Class B type standard requires integrated GPS and specific LED indicators. Class B equipment also receives all types of AIS messages. Recently Class B with SOTDMA (B+) or Class B 5W authorized to be used. The new Class B+ has been defined to bridge the gap between Class A and Class B transponders, offering some clear advantages for some types of vessels and applications. Class B+ transponders have a higher power transmission 5 Watts instead of 2 Watts, and this not only increases the range over which the vessel's transmission received, assuming proper antenna height and performance, but it also significantly improves the satellite AIS reception, enabling global tracking [11]. The detail of the AIS class comparison showed in Table 2.3 below.

Table 2.3 AIS Class Comparison

Function	Class A	Class B+	Class B
Transmit Power	12.5W	5W	2W
Transmit Rate	Up to every 2-3 secs	Up to every 5 secs	Every 30 secs
Minimum Keyboard + Display (MKD)	YES	NO	NO
Technology	SOTDMA	SOTDMA	CSTDMA
Guaranteed Time Slot Allocation	YES	YES	NO
Voyage Data	YES	NO	NO
External GPS Connection	YES	NO	NO

2.1.3 Long Range AIS

The IMO development of LRIT was initially viewed as 'technology neutral.' In the face of technological limitations at the time of deployment, technical documentation was created to allow ships to send the necessary six-hour reports to the system. As satellite AIS evolves, it is possible to look at alternate technology to adapt to the SOLAS Regulation. The initial development of AIS included a 'long-range' capability. The thought was to integrate AIS with other technologies (e.g., Inmarsat-C or MF/HF radio as part of the Global Maritime Distress and Safety System [GMDSS]) to provide a long-range function. So far, LRIT continued to develop using alternative satellite technologies that were proven at the time, which already mandated for carriage by vessels to respond to GMDSS requirements. It can be expected that as members of IMO continue to express concerns over the cost imposition of LRIT. Alternative technologies being assessed to provide the most effective means of responding to the SOLAS Chapter V's obligations, Regulation 19-1 [12].

2.1.4 AIS Application

- Collision avoidance

  AIS has been developed as a technology solution by IMO technical committees to prevent collisions between large vessels at sea that are not within the range of shore-based systems. The AIS data defines each vessel individually and its particular location and movements, which are then shown in real-time as a virtual image. A location report such as Closest Point of Approach (CPA) and collision alarms could be automatically determined based on AIS standards. Details about the passage of other ships and identity in the vicinity are essential for navigators while a vessel moves at sea. To make decisions to avoid collisions with other ships and other hazards, navigation information is needed. However, as all ships do not use AIS, AIS is commonly used in combination with radar.

  While AIS has this navigation information, some visual perception (e.g., binoculars and night vision), audio exchanges (e.g., whistle, horns, and VHF radio), and radar or Automated Radar Plotting Aid (ARPA) have been used for a long time. However, due to time delays, radar limitations, miscalculations, and display malfunctions, several possibilities of failure may occur that may result in a collision.

- Fishing fleet monitoring.

  Many authorities have commonly used AIS since the establishment of the AIS system to track and control their fishing fleet's activities. The AIS enables authorities to reliably and cost-effectively control the activities of fishing vessels along their coastline, typically within a range of 100 km, depending on the location and quality of the coastal receivers/base stations with supplementary satellite network data. Based on this AIS information, one can develop automated methods to detect potential fishing behavior from different gear types based on AIS track data [13]. In Indonesia, the joint analysis of VMS-AIS and VDS report has been carried out, leading to an estimated amount of illegal fishing in the

Arafura Sea based on the assumption that legal vessels fishing carry VMS-AIS systems [14].

- Maritime & EEZ security

  AIS data helps authorities to classify individual vessels and their activities within the national's Exclusive Economic Zone (EEZ). When AIS data is fused with existing radar systems, it is easier for authorities to distinguish between ships. To create normalized activity patterns for individual ships, AIS data can be easily processed. It was then possible to examine this pattern, which produces an alert when violated, identifying potential risks to the most optimal use of security assets. AIS also enhances understanding of the maritime domain and enables improved ocean protection and control. AIS data have also been analyzed to counter piracy in the Gulf of Aden by integrating LRIT and SAR images [15]. Additionally, AIS can be applied to freshwater river systems and lakes.

- Other Applications

  In an application such as navigation aids, AIS is often used to transmit locations and names of objects other than ships, such as navigational aid and marker locations and different types of data representing the location (e.g., currents and weather conditions). Onshore, such as in a lighthouse, sea, platforms, or buoys, these aids can be found. The message from AIS could be used by SAR vessels or aircraft in marine search & rescue operations to locate individuals in distress.

  As it provides accurate historical data on time, identity, GPS-based location, compass heading, course over land, speed (by log / SOG), and rates of turn, rather than the less accurate information given by radar, the AIS information obtained by VTS is important for accident investigation. Historical information from the message may also be used for the investigation. This includes the control of underwater seabed infrastructure accidents, such as cables or pipelines. Nowadays, AIS information is used to serve various purposes and facilitates the work of people in various occupations, such as (among others) [16]:

  - Port authorities and harbor masters
  - Ship owners, managers, and builders
  - Ship agents, brokers, and charterers
  - Researchers and data analysts
  - Tug operators and pilots
  - Search and Rescue teams

- Flag administrators and classification societies
- Vessels' crews and their families' members
- Coast guard and border patrol
- Hotels and tour operators
- Passengers or recreational sailors
- Environmental protection agents
- Maritime enthusiasts and radio-amateurs

2.2 Ship Tracking with AIS in Coastal Areas from Coastal Stations.

The Automatic Identification System (AIS) is a ship and shore-based data transmission and interrogation technology that operates in the maritime band of the VHF, enabling ships to be controlled and tracked from appropriately equipped ships and shore stations.

The AIS features and capabilities make it a powerful tool to improve knowledge of situations, thereby contributing to maritime navigation's safety and security and shipping traffic management efficiency.

The AIS system enables port authorities and coast guards to track seagoing traffic, however since its VHF signals have a horizontal range of just 20 to 40 nautical miles. It means that AIS data is only available within coastal zones or on a ship-to-ship basis [17].

The AIS coverage of the sea area within a circle of nautical miles in radius A over which the radio transmission route lies over the ocean. Radius A is equivalent to the transmitting distance between the VHF antenna of a ship at the height of 4 m above sea level and the VHF coastal station's antenna at the circle's center. The following formula should be used to calculate the range A in nautical miles:

$$A = 2.5\sqrt{H_c} + \sqrt{h_s} \tag{2. 1}$$

H_c is the height of the coast station VHF receiving antenna in meters, and h_s is the height of the ship's transmitting antenna, which is assumed to be 4 m [18].

One of AIS's advantages enables shore authorities to monitor, as required, vessels operating within their coastal waters, the designated Ship Reporting System (SRS), or the Economic Exclusive Zone (EEZ). As long as the VHF is within its range, most necessary reports should be automatically provided by all vessels fitted with AIS. The information available to the polling authority is available via a long-range message provided via the serial interface of the AIS Long Range and not through regular VHF Data Link (VDL) messages.

For connecting to long-range communication, AIS is also provided with a two-way interface. Initially, the AIS is not supposed to be able to be directly linked to such equipment. First, a coastal station will have to order the ship to transmit long-range AIS information. Any ship-to-shore communication would always be made point-to-point and not broadcast. Suppose the contact (e.g., via INMARSAT C) has been created. In that case, the ship will have the choice of setting its AIS to automatically respond to any subsequent request for ship reporting from that shore station or, as required, at regular intervals.

This functionality allows a quicker response to emergencies such as search and rescue (SAR) as well as environmental pollution response and enables the coastal state to assess the navigational requirements or improvements that may be necessary for navigational safety in such areas. Many benefits can be realized from such monitoring, such as better traffic routing, port and harbor planning, and more safety-related information exchange [19].

AIS allows quick, automatic, and accurate information on the vessel's risk of collision to be given to calculate the Closest Point of Approach (CPA) & Time to Closest Point of Approach (TCPA) from the positional data transmitted by the target vessels. AIS increases the chances of identifying other boats, even though they are in a canal or river behind a bend or in an archipelago behind an island. AIS also solves the radars' problem by detecting smaller crafts fitted with AIS in sea and rain clutter.

An AIS unit is a VHF radio transceiver capable of exchanging information with other ships and suitable receivers ashore within the VHF range, such as ship identity, position, ship direction, speed, length, ship type, and cargo information. According to a pre-determined time series, AIS transmissions consist of bursts of digital data' packets' from individual stations.

AIS is, therefore, an important addition to current systems, including radar. The information obtained through AIS enhances the information available to the Watching Officer and the Vessel Traffic Service Operator (VTSO). The International Maritime Organization (IMO) has developed carriage guidelines for merchant ships. Technical features and ratified global frequencies have been specified by the International Telecommunication Union (ITU). For global interoperability, the International Electrotechnical Commission (IEC) has also developed methods for evaluating AIS.

The continuous operation of AIS brings many benefits to the shore authorities, as in Figure 2.2, automatic and immediate provision of the ship (such as MMSI, call sign) and location, enabling, where available, rapid radio communication. This advantage is of equal, if not more significant, importance to the authorities of the VTS. When approaching or entering the VTS location, VTS organizations require vessels to report to the VTS center. VTS centers have to rely on vessels that report both identity and location to the VTS center without AIS. The VTS operator then compares this data with, say, an unassigned radar target.

The method of identification is time-consuming and entirely dependent on the cooperation of participating vessels. It is not unusual for ships to fail to comply with this requirement unintentionally, thus creating a potentially dangerous situation and creating unnecessary distractions for the operator of the VTS. The VTS traffic image relies on vessels reporting identity through VHF, even where VHF direction-finding equipment is equipped, thus enabling identity to be associated with the track acquired. AIS helps to resolve the shortcomings and time-consuming processes inherent in the existing arrangements in this situation.

The organization of the VTS is equipped with such equipment capable of obtaining both the identification and the exact location of a vessel at the full reception range of the frequency of VHF radio contact. It also enables the identification of targets far outside the traditional radar range in this case. Due to the need to screen base stations from neighboring VHF interference, even when this is not feasible, extended VTS detection range can be accomplished by adding base or repeater stations linked to a network at a much lower cost than radar.

AIS provides many benefits, including increased situational awareness, improved navigational safety, maritime security, and automatic reporting in mandatory and voluntary reporting schemes. It also enhances certain areas of the ship to shore and shore to ship communications, including the efficiency of shipping and port operations. AIS provides a means of monitoring aids to navigation and to exchange safety information. AIS complements other resources for situational awareness to have a standard operational procedure and allows the collection of accurate information on ship traffic [20].

In the case of VTS, AIS will specifically allow automated ship reporting and enhance navigational safety by providing enhanced traffic situation data, including vessel locations, movement, identities, and destination. It also produces, including meteorological and hydrological conditions, a fairway situation. Concerning navigation aids, AIS could complement existing navigation aids. Data such as local and regional navigational warnings, real-time tidal heights, tidal streams, and local weather are also provided. AIS also provides Aids to Navigation (AtoN) reliability monitoring. In SAR operations, AIS provides improved coordination of SAR assets during the response phase. There are additional regional benefits, such as ice breaker operation management [20].

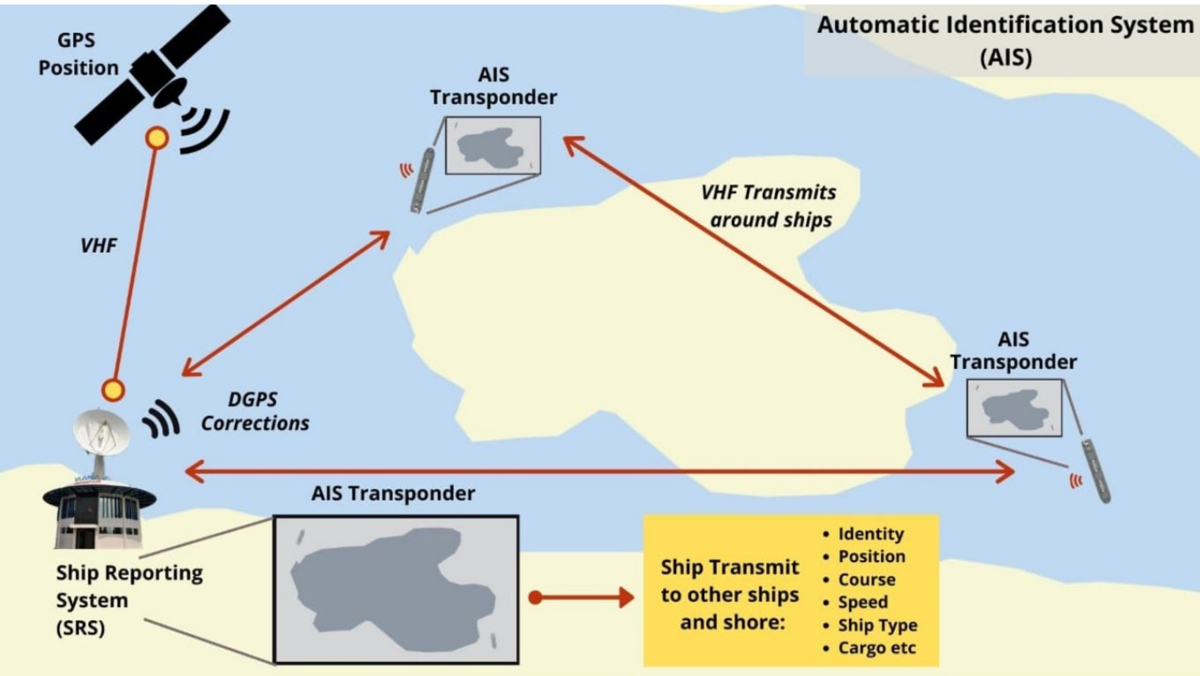

Figure 2.2 AIS in the shore area.

The maritime authority has started to make use of the AIS benefits by [21]:

- Implement the AIS required infrastructure (shore-based AIS stations, VTS core, services),
- Implementation of AIS in traffic control centers and, besides operate the coastal network of AIS,
- Enable other facilities to be interconnected, such as SAR, reporting, port authorities, etc.

AIS traffic monitoring can be quite different within different sea areas due to different traffic intensity and risks:

- High-density ocean areas (approaches, ports, radar surveillance frequently available): AIS data support/significant complement of radar target tracking.
- Medium traffic density (not typically available for radar monitoring so far): AIS will allow high-quality traffic monitoring, i.e., e-visual tracking in VTS centers and automated warnings where cross-track or off-track limits are crossed for a specific passage.

- Sea areas with low density (remote areas): AIS data can be used for automated traffic monitoring.

In all cases, as mentioned above, AIS data – received by the VTS center – provides information about potential critical situations and allows early and appropriate action. In the high traffic area such as the Baltic Sea Area, the Helsinki Commission has approved to enhance the use of AIS by requiring the Governments of the Contracting Parties to establish:

- national land-based systems, based on AIS signals,
- a common Baltic Sea monitoring system based on – and with access to – all national Baltic AIS monitoring systems.

Full monitoring of the Baltic Sea Area (within A1 sea area) shall not occur later than 1 July 2005. An expert working group is working on procedures to ensure that each national AIS system can be linked to the AIS systems of the other Baltic States [22].

With marine traffic growing, Vessel Traffic System (VTS) is now playing an increasingly important function. AIS data analytics framework also could be used to facilitate operation management, aiming to further improving the efficiency of VTS and finally ensure the safe and smooth maritime traffic environment. Using historical traffic analytics, one could extract valuable spatial-temporal data from vessel kinematics records and make a statistical analysis [23].

Estimating the vessel times of arrival in port areas could also be done using a data-driven path-finding algorithm. This could be done by exploiting historical ship reporting systems data using historical AIS and LRIT maritime traffic data over a desired area of interest. The performance gain obtained by considering the knowledge extracted from historical data reveals that the traffic is more structured [24].

By using AIS data, a smart port as the last generation of the traditional seaport, which is reinforced with new technologies such as IoT, could be defined in detail as well as its architecture and challenges [25].

2.3 Filling the Gap Over the Oceans by Use of Satellites

Recently, there has been a growing interest in detecting and monitoring ships at distances from coastlines larger than standard terrestrial VHF communications can reach. Like the requirements of these long-range applications, such as better handling of dangerous cargo, improved protection, and combating illicit operations, the need to detect ships very far away from shores was considered. As a promising approach to address the limitation of terrestrial VHF coverage, satellite-based AIS is provided with the ability to provide AIS detection service coverage on any given area of the earth.

The footprint of the satellite-based AIS could be defined as follow:

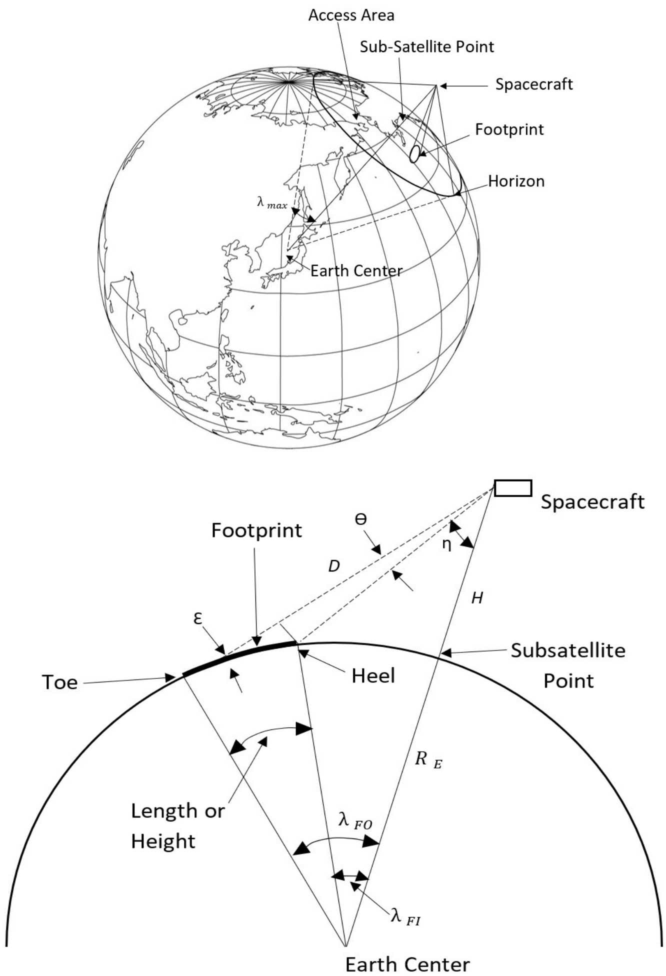

Figure 2.3 Geometry for instrument footprint. (adapted from [26])

As Figure 2.3 shows, the satellite footprint is normally a beam with a circular cross-section substantially smaller than the access area projected onto the earth's surface. However, since satellite AIS (S-AIS) typically uses the omnidirectional antenna, the term footprint and access area in the above figure is the same. The length (or height) of the footprint could be calculated as:

$$L_F = K_L(\lambda_{FO} - \lambda_{FI})$$
$$= D \ \sin\theta \,/\, \sin\varepsilon \tag{2.2}$$

where K_L= *111.319 543 km*

To find the footprint width, W_F, is given by:

$$W_F = R_E \sin^{-1}(\frac{D \sin\theta}{R_E})$$
$$= D \sin\theta \tag{2.3}$$

Where radius of the earth is R_E=*6378.14 km*, θ is the beam width, and D is the distance from the spacecraft to the toe of the footprint.

By assuming that projection on the ground is an ellipse, then the footprint area F_A of satellite AIS is given by:

$$F_A = (\frac{\pi}{4}) L_F W_F \tag{2.4}$$
$$= \left(\frac{\pi D^2}{4}\right) \sin^2\theta / \sin\varepsilon \tag{2.5}$$

Considering that observation of AIS signal from space has the benefit of worldwide ship monitoring, several projects funded by ESA and the European Commission and private initiatives are currently undergoing to analyze the concept of satellite reception of AIS signals [27]-[31]. Some trials have also been carried out. Satellite-based AIS has to face additional technical challenges that were not considered in the original AIS standard (ITU-R M.1371-2), i.e.,

i) Colliding messages from ships transmitting from different SOTDMA cells,
ii) Relatively high carrier Doppler,
iii) Lower signal to noise ratios and
iv) Longer relative propagation channel delay among the population of ships invisibility at any given time. All these issues require particular care in the overall system design [27].

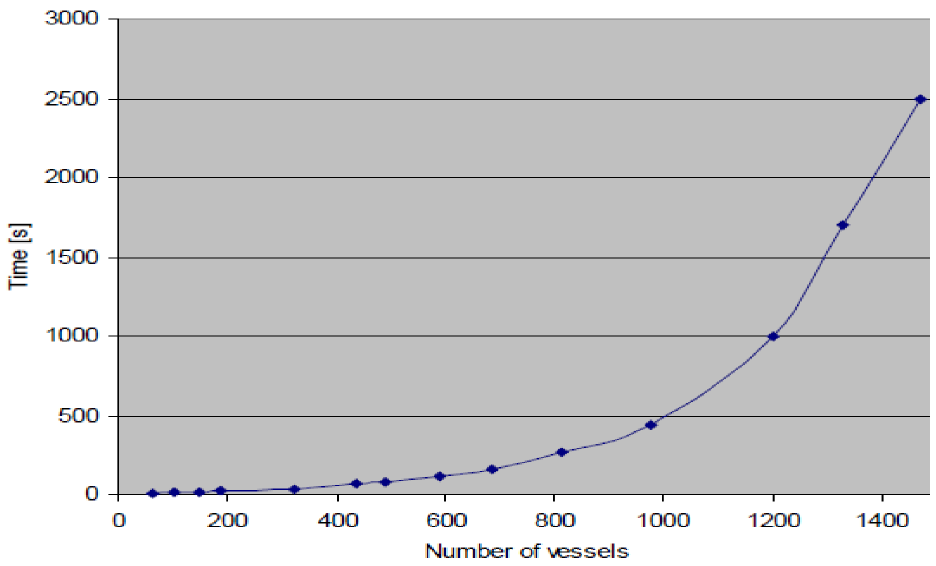

Figure 2.4 Observation time and detection probability [32].

Detection probability of satellite AIS carried out with the simulations uses sun-synchronous orbits, a satellite altitude of 600km, a receiver sensitivity of -117dBm, a D/U of 10dB, and a single quarter-wave monopole antenna. Figure 2.4 shows the required observation time to achieve a 95% detection probability due to the number of vessels seen by the satellite. A space-based AIS receiver can at most have 1,200 vessels within its field of view and still have acceptable performance before message collisions become a significant problem [32]. Besides that, there are other reports on simulations and other enhancement requirements on AIS signal collision received from space-based AIS [33] - [35].

As described before, shortly before the year 2000, the AIS was developed for terrestrial ap plications. Although AIS technology meets its initial expectations well, the emerging time and space technologies have created new opportunities, priorities, and challenges. In 2008, Orbcomm launched the first satellite constellation, Orbcomm-QL, with AIS receivers on board as a secondary payload, followed in 2009 by LuxSpace [36], and many universities, research institutes, and satellite companies since then. It has become a very common payload for small satellites because even marine commercial AIS equipment with a small antenna can receive data in space [37]. A commercial company such as ExactEarth, already provide AIS data collected from space to maritime and security organizations [38].

This challenge of above AIS reception from space has been considered by doing several experiments and changing the design of AIS receiver, antenna, and also with the constellation of several satellites. From 2010 to date, several satellites have been launched with further improvement of AIS detection from Space [29], [32], [39], [42]. Its is also including a Flying Laptop satellite that also carries AIS and optical Images launched in 2017 [104].

Satellite AIS has the opportunity to provide a new concept of maritime domain awareness, and it also has some unique applications that support both mariners and authorities. Although coastal AIS can assist some of these same use cases, it has a major range restriction that can restrict an authority's ability to plan for off-shore structures dependent on waterway use, organize responses, take compliance action, and prepare logistics.

Satellite AIS system support at least two important tasks, as follows [43]:

2.3.1 Ship Reporting

Many countries run Voluntary Ship Reporting (VSR), with coverage reaching over extensive ocean areas. VSR helps Search and Rescue Authorities (SAR) to understand better where ships are in their SAR area. While SAR is the purpose behind voluntary ship reporting, the information can be used for many other purposes by different authorities.

Voluntary ship reporting involves numerous sets of information that include both dynamic and static hull and cargo information. This information can currently be submitted via Telex or email and meets the guidelines of IMO. Anything from a few hours to days is the reporting interval. After the cargo and passage plan, information is received by the authority, location reports (ID, Location, Direction, and Speed) are periodically needed. It can be troublesome to rely on these being entered and sent manually.

The use of satellite AIS in voluntary ship reporting offers many advantages, both from a cost-saving and safety and environmental viewpoint, to ship owners and operators and the maritime authorities. This allows:

- More effective planning and allocation of resources for SAR and pollution prevention;
- More consistent and automated reporting systems to identify possible vessel problems earlier;
- A reduced reporting cost for ship owners.

Applications for port state control need a listing of ships that are in infringement of SOLAS requirements or need to be repaired but have been permitted to leave port. By the use of satellite AIS, it is possible to track the approach of these vessels and, if necessary, to deploy additional assets to escort or intercept these ships prior to pose a risk to coastal waters.

2.3.2 *Monitoring of Fishing & Specific Interest Area*

A vessel monitoring system (VMS) controls many of the fishing activity. Information about the vessel's location and operation is provided by the equipment mounted on fishing vessels; VMS location reports are needed every 2 hours. However, Satellite AIS is a passive system requiring nothing more than a Class A system that is mounted on a fishing vessel. The information provided in the standard location report offers details on velocity and heading. Also, the satellite AIS generates higher data quality from the first pass detection, the more likely multiple position reports for any given target. Current VMS data enhanced with satellite AIS data will provide an accurate analysis of the fishing fleet's worldwide behavior. In a country like Indonesia, with a large fishing zone area, AIS information combined with PFZ (Potential Fishing Zone) information that resulted from remote sensing data to get the behavior information of fishing vessel [44].

In order to protect offshore installations and reduce the risk of a maritime casualty and resulting marine pollution, some exclusion zones and precautionary areas usually have been established. Precautionary areas can include wind farms or oil and gas fields and may refer to vessels of a particular size. Vessels may be forbidden to enter other parts of the sea because of environmental concerns. Any vessel wishing to enter such areas may only do so after clearance by the mandatory reporting system for the area concerned.

Other areas may be restricted or tightly controlled or allow endangered marine species and organisms to thrive or recover due to ecological crises. These areas can be monitored with satellite AIS for particular infringements and trends of ship populations. Satellite AIS can give such as information:

1. A report of all vessels that appear to be moving into sensitive areas on their path. A ship attempting to pass or avoid such an area will not be aiming for it directly but will have the best safe route to avoid it.
2. A report on vessels such as tankers that have deviated from their "course," which may mean that they are attempting to prevent dumping tank slopes from being identified.
3. A report on vessels that have strayed into remote, sensitive areas away from coastal surveillance installations.
4. Authority's ability to broaden their sensitive areas beyond which they can track the use of coastal facilities and other essential details that could be supplied by the AIS seashore.

Satellite AIS is a technology that, in combination with other sensors and technologies currently in use, improve overall wide-area maritime domain awareness. While the initial AIS system was designed and deployed to improve maritime protection and strengthen near-shore VTS capability, it has substantial limitations of coverage, which requires large investments in monitoring a wider area. Nevertheless, satellite AIS can provide comparable detection efficiency for fill-in coverage of remote coastal areas and offers full global coverage with comparable average detection output but with the downside of periodic vessel detection update (i.e., many times a day). Therefore, for complete wide-area maritime domain awareness, both AIS systems are required.

3

LAPAN Satellites for Maritime Surveillance

Since 2012 LAPAN developed two satellites called LAPAN-A2 and LAPAN-A3 satellites. Those satellites in the initial plan aim for equatorial orbit called twin satellites [45]. However, due to several project considerations and launch failure risk, those satellites are separated in different launch time and orbit. This section describes both LAPAN-satellites launched and serves a maritime surveillance mission & other mission.

3.1 LAPAN-A2 Satellite

LAPAN-A2 is the microsatellite developed after the LAPAN-A1/LAPAN-TUBSAT satellite successfully launched and operated since 2007 [46].

The missions of LAPAN-A2 are [47]:

- Earth observation video surveillance based on the LAPAN-TUBSAT mission.
- Experimental Space Digital Camera.
- Maritime monitoring using AIS (Automatic Identification System).
- Supporting Amateur Radio with Voice Repeater and APRS (Automatic Position Reporting System) for disaster mitigation.

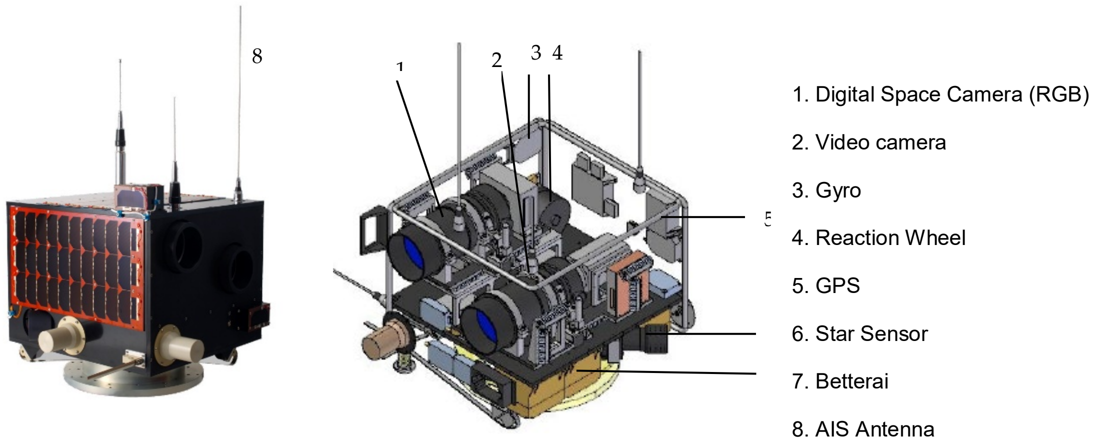

Figure 3.1 LAPAN-A2 Satellite.

Figure 3.1 shows that the satellite brings analog color video camera payloads with 1000mm focal lengths and digital cameras with 1000mm focal lengths with less pixel size. AIS and other metadata are downlinked by S-Band digital transmission. Video camera payload data acquired by satellite in orbit outside ground station coverage could be recorded on solid-state memory as a digital file and transmitted later on to the ground station. Since this is a multimission satellite with many payloads onboard, this is one of the compact microsatellites.

Since Indonesian territory spread along the equator, the satellite's operation at low inclination orbit is needed. The satellite may pass Indonesia as much as SSO orbit pass the North/South pole (14 times in 24 hours at 600 km orbit). The inclination of 10^0 is needed to cover Indonesia's area with a surveillance camera oriented at nadir. Therefore, when ISRO announce that it would launch the ASTROSAT mission, which has an orbit of 650 km circular at an inclination of 6^0, LAPAN decided to put the satellite as auxiliary payloads for the mission. With many passes over Indonesia, the missions more useful. LAPAN-A2 satellite launched as an auxiliary payload on the Indian Space Research Organization (ISRO) Polar Satellite Launch Vehicle (PSLV) C-30 on 28 September 2015 at 10.00 local time.

3.1.1 LAPAN-A2 Payload Configuration

For supporting the LAPAN-A2 satellite mission, the LAPAN-A2 payload is designed to carry High-Resolution Space Camera, Automatic Identification System (AIS), Automatic Packet Radio System (APRS), and Voice Repeater for amateur communication. A block diagram of the LAPAN-A2 payload can be seen in Figure 3.2.

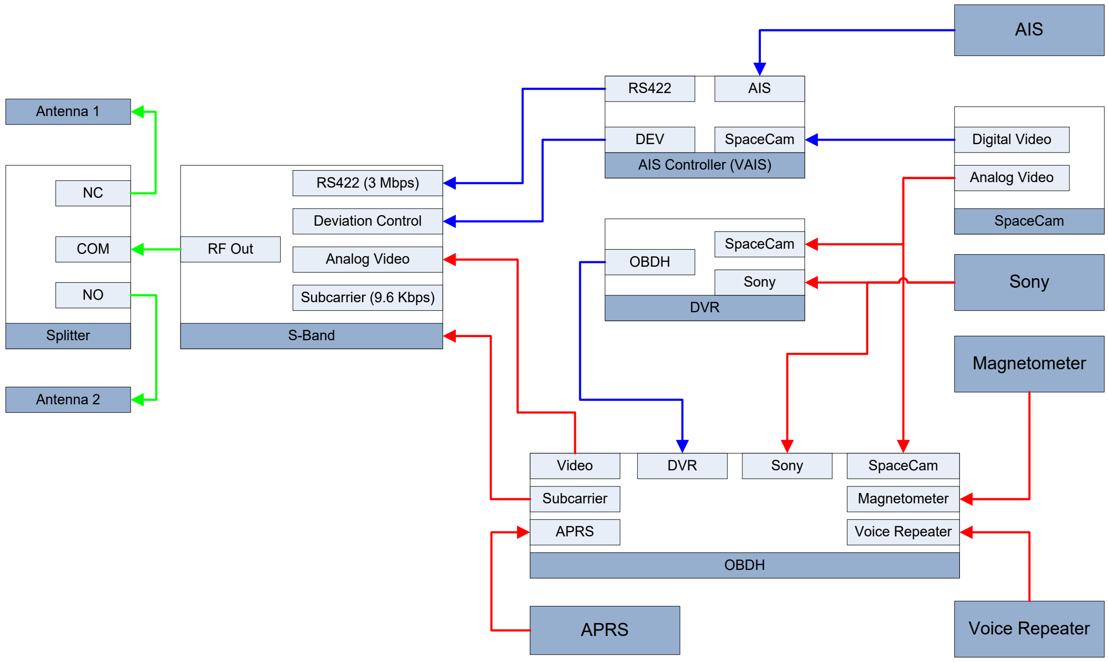

Figure 3.2 LAPAN-A2 payload block diagram.

The space camera payload is a high-resolution digital camera with a 1000 mm focal length. The camera has 2000 by 2000 pixels with 12-bit digitalization. The square pixel with a small size of 5.5 µm x 5.5 µm and the high image resolution of 4 megapixels is optimally qualified for all space imaging applications, particularly for high ground resolution earth observation.

Another camera is typically the same as the camera of LAPAN-TUBSAT. This camera is an analog video camera with a three-chip CCD with a prism beam splitter as a color filter and Exwave HAD Technology, enhancing video signal/picture. The CCD chips have a 752x582 active pixel area, which with the 1000 mm lens, is translated into the ground resolution of 3.5 m and 7 km swath. The power consumption of the camera is 7,6 Watt (12 V; 0,66 A). The difference with the LAPAN-TUBSAT video camera was LAPAN-A2 has the additional feature of video and image recorder onboard, so video or image taken could be done out of ground station coverage automatically.

This satellite also carries a high sensitivity spaceborne AIS receiver to detect all AIS signals from ship mostly in the equator region. Many AIS signals could be detected in an area. The AIS receiver used in LAPAN-A2 is similar to AISSat-1 and AISSat-2 satellite AIS receiver. Its prototype has been tested in ISS. It is a software-defined radio (SDR), as indicated in Figure 3.3. For further hardware processing, the AIS signal is sampled and forwarded to the FPGA. The reprogrammable FPGA feature allows the AIS sensor to be fine-tuned in-flight based on the analysis of obtained AIS data or allows the FPGA to be fully reprogrammed to take advantage of substantial potential design and functionality improvements. [32].

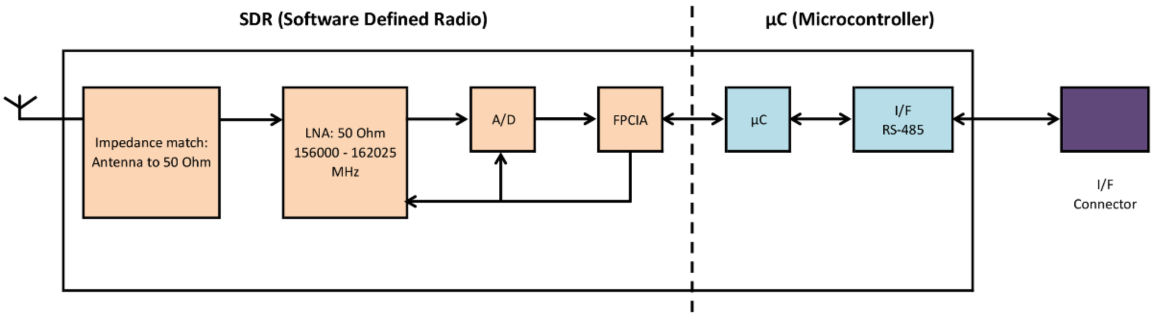

Figure 3.3 receiver block diagram.

Features of the AIS receiver onboard LAPAN-A2 as follows:

- Simultaneous reception and decoding of any two channels in the maritime VHF band
- SDR-based radio architecture-upgradeable after launch
- High sensitivity
- Low power consumption
- Industrial grade components used giving a cost-efficient AIS payload
- RS422 interface
- Max ship message: Single Timeslot reception of 156 msgs/sec and dual Timeslot reception of 92 msgs/sec
- Data rate : 57.6 kbps
- Frequency range: Channel A 161.975 MHz & Channel B 160.025 MHz
- Sensitivity : -117 dBm
- Dynamic Range : (-90) – (-117) dBm

This payload is very useful for monitoring Indonesian flagship or other ships worldwide, as Indonesia is globally the largest archipelago. Its territorial water is about 5,8 million km^2 of 75% from its territory. International Maritime Organization (IMO) has defined that the sea route through Indonesian territory from Malaka strait down to Sunda Strait is the 1st international safe passage. The route through Sulawesi strait down to Lombok strait as the 2nd international safe passage. Due to that, many ships passed the Indonesian seas daily.

With the advantage of 14 times a day revisit, LAPAN-A2 can record and detect all AIS signal in 90 minutes in the equator region. To achieve this, spaceborne AIS was equipped with a 4 Gbit solid-state recorder, a huge memory for recording only AIS data. It is enough to record typically one month of AIS data without re-written.

LAPAN-A2 also carries two amateur payloads: a voice repeater and an Automatic Packet Reporting System (APRS) repeater. Voice repeater in the LAPAN-A2 satellite uses VHF frequency for downlink and UHF frequency for uplink with tone decoder. The APRS repeater in VHF frequency is used for text messaging repeater, sent by APRS operator in one location to other locations, or broadcasting emergencies by text messaging. In times of crisis and natural disasters, amateur radio is often used as a means of emergency communication when wireline, cell phones, and other conventional means of communications fail. By using those repeaters in satellite, the coverage increase to more than 2500 Km. Increasing coverage would be beneficial for supporting communication during disaster mitigations [48].

3.2 LAPAN-A3 Satellite

Besides the LAPAN-A2 satellite, LAPAN also developed LAPAN-A3 or also known as LAPAN-IPB, by involving cooperation with Bogor Agricultural University (IPB) as in Figure 3.4. The LAPAN-A3 satellite project's objective is to achieve the microsatellite's design, integration, and operation in Indonesia. LAPAN-A3 primary mission is Earth Observation with four bands, a Multispectral line scan imager, and Space Digital Camera. The satellite also carries AIS (Automatic Identification System) receiver to monitor global maritime traffic, a scientific magnetometer for Earth Magnetic Field observations, and a star sensor made by LAPAN for space qualification [49].

LAPAN-A3/IPB was launched on June 22, 2016 (03:56 UTC) as a secondary payload to ISRO's CartoSat-2C spacecraft. The launch site was Satish Dhawan Space Center in India, and the launch vehicle was PSLV-C34 [50].

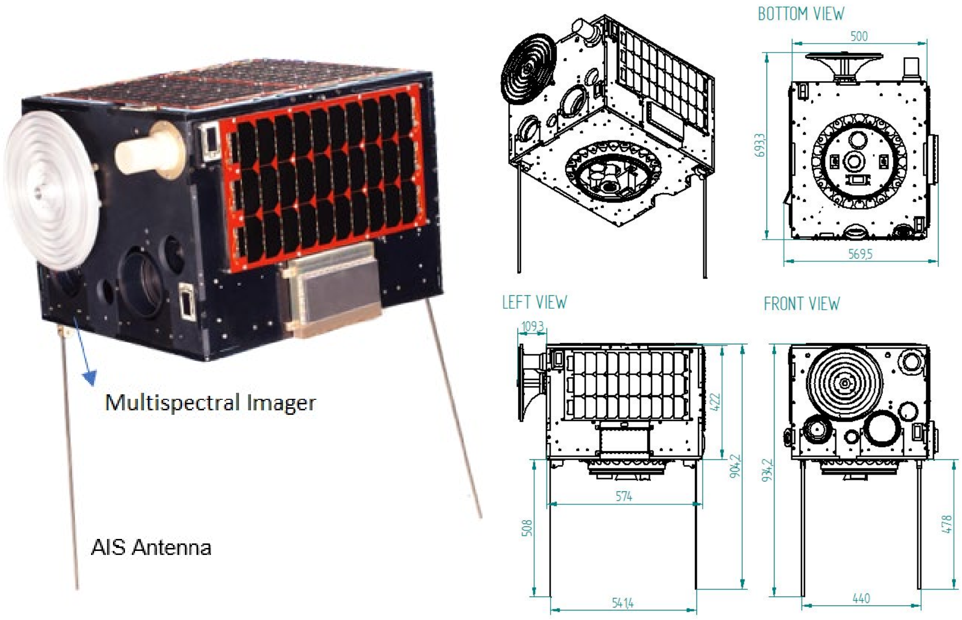

Figure 3.4 LAPAN-A3 Satellite.

LAPAN-A3 satellite carries a line scan multispectral imager consisting of 4 spectral bands: visible green, red, blue, and Near Infra-Red (NIR). The spectrum of each line is similar to the LANDSAT satellite band type. The Bogor Agricultural University (IPB) recommends those spectral bands used in LAPAN-A3. These four spectral bands could achieve most land cover, forestry, agricultural, and other remote sensing user needs in Indonesia.

The red, green, and blue spectral channels could be used for a “true color” image. However, a combination of this visible spectral band with a near-infrared channel could produce a “false-color composite” image. This false-color composite scheme allows vegetation to be detected readily in the image. In this type of false-color composite image, vegetation appears in different red shades depending on the vegetation's types and conditions since it has a high reflectance in the NIR band. The installed sensors in LAPAN-A3 can present data about the seasonal agricultural field, especially rice, with data emphasis on rice growing phases and estimation of the harvest area and beginning of the harvest season [44]-[47].

The size of each band line consists of 8023 pixels. This line imager camera uses a 300 mm lens and an altitude of 505 Km, so it has ~15 meters resolution with ~120 Km swath of image. Besides the multispectral line scanner imager, LAPAN-A3 also carries a Space Digital Camera with a 1000 mm lens, 2048x2048 pixels, with ~3.5-meter resolution with ~7 Km swath. This image is used for line imager calibration and a more in-depth look at the interesting spot on the ground.

LAPAN-A3 also carries AIS (Automatic Identification System) receiver to monitor ship traffic in the polar region. The maritime traffic monitoring, was that moment, still counting on the coastal stations and patrol boats. The range of the coastal station is typically 40 nm and about the same for patrol boats. Therefore, the coverage for Indonesian waters is still limited. The limitation brought many maritime law violations and reduced the safety level of Indonesian water. Therefore, for Indonesia, using a satellite-based maritime surveillance system is one of the best solutions. By positioning the AIS receiver on the satellite, its coverage is wider than that typically positioned seashore's maritime authority.

3.2.1 LAPAN-A3 Payload Configuration

As a multimission satellite, LAPAN-A3 carries several payloads as follows:

- AIS Receiver
- 4 Bands Multispectral Imager
- Space Camera (Digital Camera)
- Magnetometer

As seen in Figure 3.5, those payloads are connected to the payload data handling unit, which then records and transmits the data to the ground. Also, the payload data handling could transmit the data in real-time through its 105 Mbps X-band transmitters. The payload data handling and a transmission scheme for LAPAN-A3 follow a CCSDS standard [55].

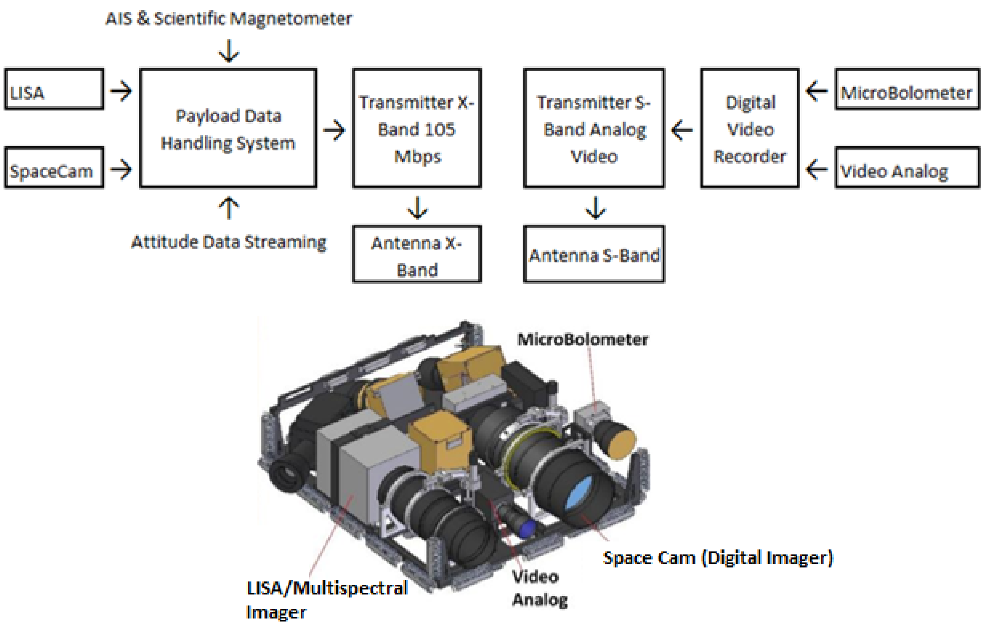

Figure 3.5 LAPAN-A3 payload block diagram and optical payload compartment.

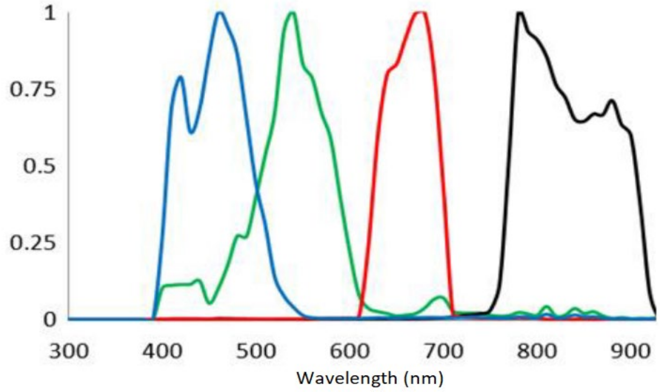

Figure 3.6 Normalized spectral response of LAPAN-A3 multispectral imager [56].

The spectral response from each CCD line of LAPAN-A3 multispectral imager is shown in Figure 3.6. The figure shows each spectral response of each CCD line sensor, including its spectral filter. Several pre-flight tests were carried out to generate a radiometric model for radiometric correction of the multispectral imager in LAPAN-IPB Satellite on-orbit [56].

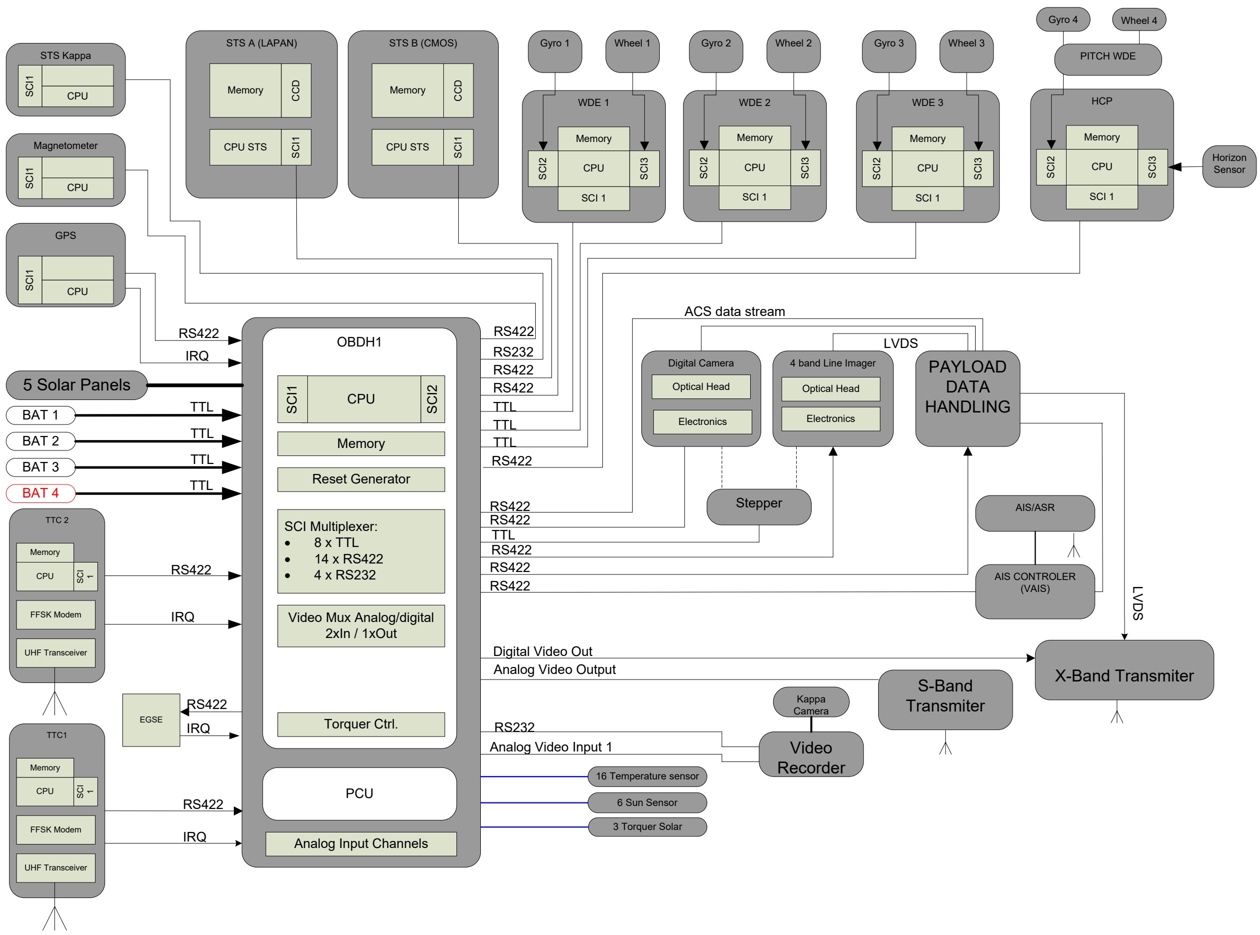

Figure 3.7 LAPAN-A3 satellite block diagram.

As seen in Figure 3.7, the AIS receiver connected through its recording unit, called the AIS controller, which same as in LAPAN-A2 with 8 Gbit recording and a data stream of 3 Mbps. This data then transmitted to payload data handling and store for transmission through the X-band transmitter. The receiving station of LAPAN-A3 satellite data uses antenna size with a diameter of more than 5.4 meters [54].

3.3 LAPAN Satellite AIS Data

3.3.1 AIS Structure

Space-based AIS onboard of both LAPAN-A2 and LAPAN-A3 satellites has the same AIS structure data formatting, as in Figure 3.8.

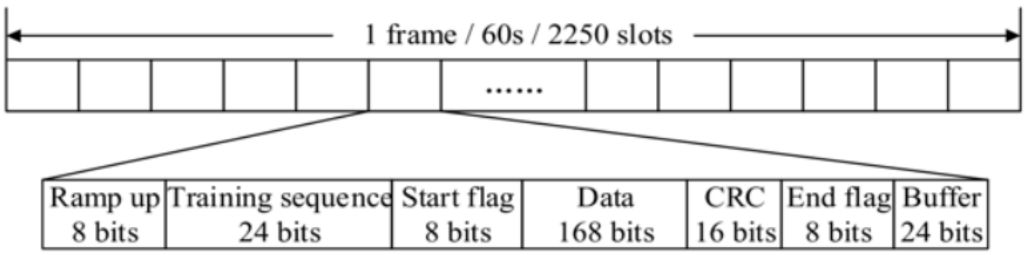

Figure 3.8 AIS data structure [8].

From the structure, the LAPAN-AIS satellite could receive a maximum of 2250 data slots every second with 26.7 ms transmission time for each message. Those AIS receivers transmitted from the ships in the footprint of the satellite-based on its status of navigation, as described in the previous section.

Table 3.1 Main Data Format of AIS data received by Satellite [9]

Parameter	Definition
CRC (Uplink/Downlink)	CRC for AIS Data
Time	Time AIS received by Satellite
RSSI	Received Signal Strength Indicator
FSI	Frequency Offset Indicator
Message Type	Message type according to ITU definition
Repeat Indicator	Used by the repeater to indicate how many times a message has been repeated.
MMSI	Maritime Mobile Service Identity (Ship Identity)

Navigation Status	0 = under way using engine, 1 = at anchor, 2 = not under command, 3 = restricted maneuverability, 4 = constrained by her draught, 5 = moored, 6 = aground, 7 = engaged in fishing, 8 = under way sailing, 9 = reserved for future amendment of navigational status for ships carrying DG, HS, or MP, or IMO hazard or pollutant category C, high speed craft (HSC), 10 = reserved for future amendment of navigational status for ships carrying dangerous goods (DG), harmful substances (HS) or marine pollutants (MP), or IMO hazard or pollutant category A, wing in ground (WIG); 11 = power-driven vessel towing astern (regional use); 12 = power-driven vessel pushing ahead or towing alongside (regional use); 13= reserved for future use, 14 = AIS-SART (active), MOB-AIS, EPIRB-AIS 15 = undefined = default (also used by AIS-SART, MOB-AIS, and EPIRB-AIS under test)
Rate of Turn (ROT)	0 to +126 = turning right at up to 708 deg per min or higher 0 to -126 = turning left at up to 708 deg per min or higher Values between 0 and 708 deg per min coded by ROT_{AIS} = 4.733 SQRT(ROT_{sensor}) degrees per min where ROT_{sensor} is the Rate of Turn as input by an external Rate of Turn Indicator (TI). ROT_{AIS} is rounded to the nearest integer value. +127 = turning right at more than 5 deg per 30 s (No TI available) -127 = turning left at more than 5 deg per 30 s (No TI available) -128 (80 hex) indicates no turn information available (default). ROT data should not be derived from COG information.
Speed over Ground	Speed over ground in 1/10 knot steps (0-102.2 knots) 1 023 = not available, 1 022 = 102.2 knots or higher
Position Accuracy	The position accuracy (PA) flag should be determined in accordance with the table below: 1 = high (<= 10 m) 0 = low (> 10 m) 0 = default
Longitude	Longitude in 1/10 000 min (+/-180 deg, East = positive (as per 2's complement), West = negative (as per 2's complement).

	181= (6791AC0h) = not available = default)
Latitude	Latitude in 1/10 000 min (+/-90 deg, North = positive (as per 2's complement), South = negative (as per 2's complement). 91deg (3412140h) = not available = default)
Course Over Ground	Course over ground in 1/10 = (0-3599). 3600 (E10h) = not available = default. 3 601-4 095 should not be used
True Heading	Degrees (0-359) (511 indicates not available = default)
Time Stamp	UTC second when the report was generated by the electronic position system (EPFS) (0-59, or 60 if a timestamp is not available, which should also be the default value, or 61 if the positioning system is in manual input mode, or 62 if electronic position fixing system operates in estimated (dead reckoning) mode, or 63 if the positioning system is inoperative)
Maneuver Indicator	0 = not available = default 1 = not engaged in a special maneuver 2 = engaged in a special maneuver (i.e., regional passing arrangement on Inland Waterway)
Spare	Not used. Should be set to zero. Reserved for future use.
RAIM Flag	Receiver autonomous integrity monitoring (RAIM) flag of electronic position fixing device; 0 = RAIM not in use = default; 1 = RAIM in use.
Radio Status	Communication state based on ITU-R M.1371-5 Table 49

As typical class A AIS position report in Table 3.1, those AIS messages from ships received collected, and metadata such as timestamp, signal strength (RSSI), frequency offset, and new CRC stamp of each message were recorded by the AIS receiver onboard. There are four types of CRC flags, as in Table 3.2, that included in the AIS reception that used to check the integrity of each AIS message during the reception to transmission to the ground.

Table 3.2 CRC Config in LAPAN-AIS Data

CRC	Meaning
10	uplink true, downlink true
00	uplink false, downlink true
01	uplink false, downlink false
11	uplink true, downlink false

The uplink flag means the integrity of embedded AIS messages transmitting from the ship received by satellite. If this CRC flag is valid, then the AIS message from the ship is valid. The downlink flag means the integrity of AIS messages recorded by the AIS receiver onboard and transmitting to the ground. If this CRC flag is valid, then the transmission of the AIS data from the satellite to the ground is valid. LAPAN-AIS data that contain false either in uplink or downlink flag usually not use directly as original data. However, those false messages being collected and corrected if still possible. The simple way to correct those AIS messages by using interpolation and extrapolation algorithms for those wrong CRC flag messages. By using this simple method, 22,6% bad CRC from LAPAN-A2 dan 20,8% bad CRC from LAPAN-A3 could be corrected [57].

3.3.2 LAPAN-A2 AIS Data

LAPAN AIS data was received two months after the launch. AIS data received from satellite around 12-18 million messages with around 500000 MMSI per month. This amount of data is quite significant since it acquired about 84% of ships worldwide [58].

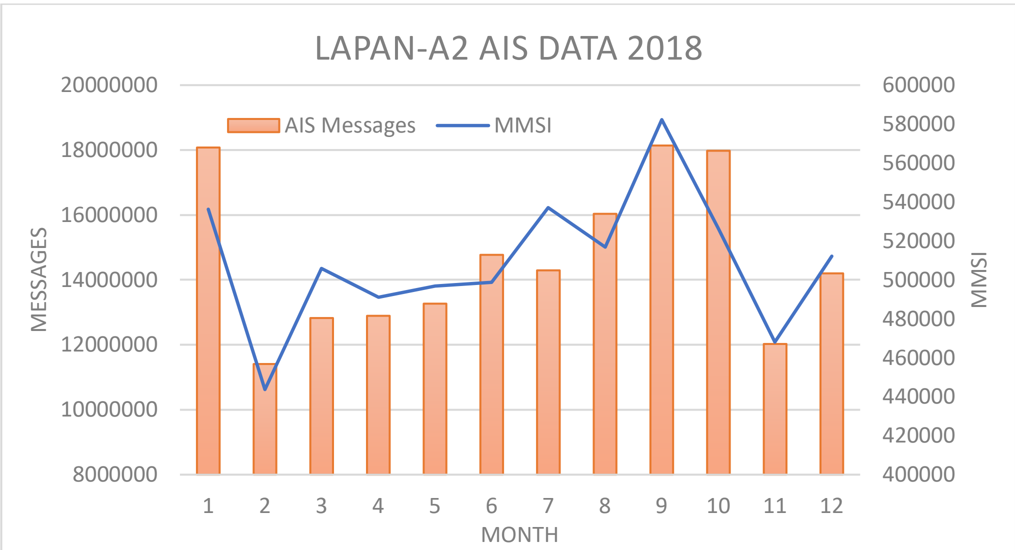

Figure 3.9 LAPAN-A2 AIS data 2018.

Figure 3.9 shows that AIS data each month vary. This variation sometimes happens due to ~14 days timer that reset all the satellite functions to default. Hence AIS receiver was off during that time. The other problem may arise from the reception of the data in the ground station or conflicting data downloading between image or AIS data.

The above data shows that one could filter the number of MMSI received by the LAPAN-A2 satellite in Figure 3.10.

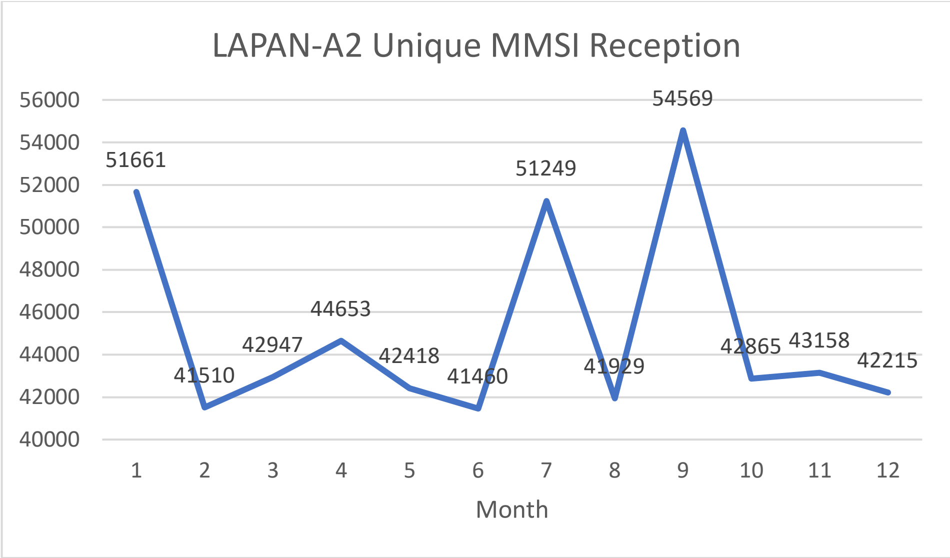

Figure 3.10 LAPAN-A2 distinct MMSI reception (2018).

In a month of AIS statistical data, every minute, LAPAN-A2 satellite collected 460 messages on average and 2270 at maximum [58]. Comparing with the AISsat-1 and AISsat-2 satellite that uses the same type of receiver, the LAPAN-A2 Satellite reception was around 10% less [59]. The reason for less data reception compares with those satellites since LAPAN-A2 is orbiting in the equatorial region that different from those satellites in polar orbit, so the north and south side of the earth is not covered as in Figure 3.11.

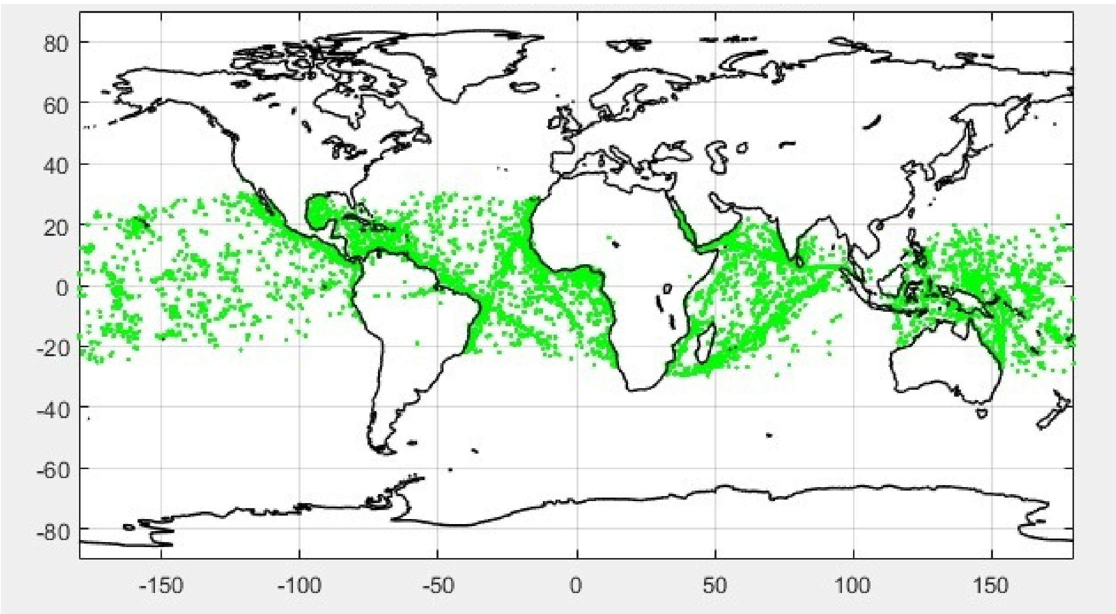

Figure 3.11 LAPAN-A2 typical data coverage.

Figure 3.11 shows that the coverage area of LAPAN-A2 with the inclination of 6 deg orbit could cover +22 deg and -22 deg latitude. The data received from this satellite shows that LAPAN-A2 could receive about 80% of the world's ship traffic. It has also shown that with this typical satellite orbit, one could monitor most of the busy ocean every 90 minutes.

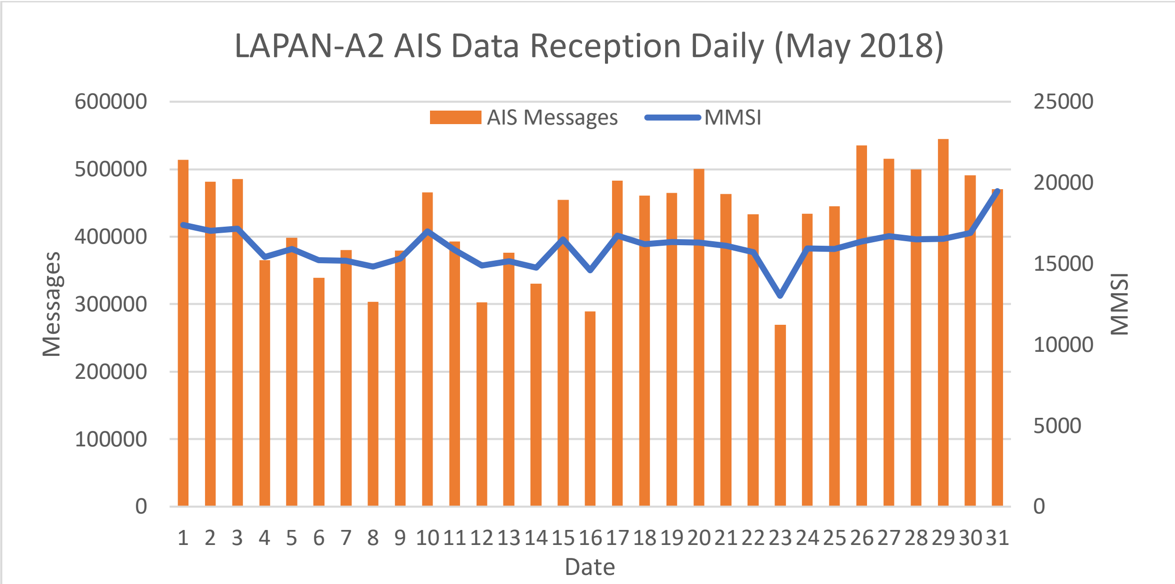

Figure 3.12 LAPAN-A2 AIS data daily. (May 2018)

Figure 3.12 shows the daily reception of LAPAN-A2 of AIS messages between 300000 to more than 500000 per day. The typical unique MMSI between 14000 to 19000 ships per day could be recognized.

3.3.3 LAPAN-A3 AIS Data

Since LAPAN-A3 orbiting in polar orbit, then it has a chance to receive the AIS signal globally. However, the satellite altitude is 505 Km, which reduces its AIS signal's footprint area compared with the LAPAN-A2 Satellite.

LAPAN-A3 AIS receiver activated two months after launch. AIS data received from satellite around 1,2-1,8 million messages with around 500 thousand MMSI per month.

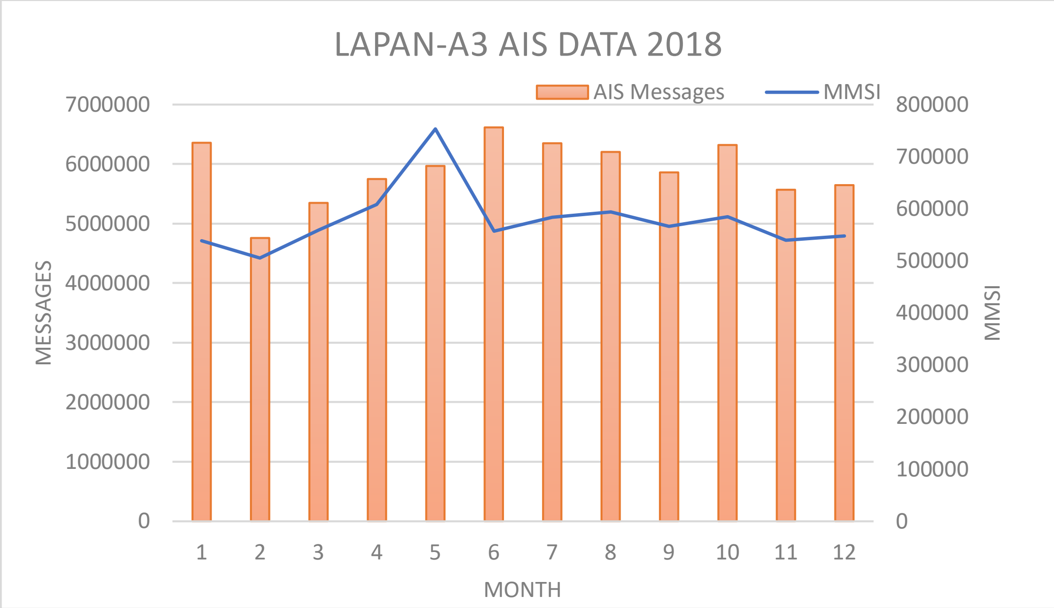

Figure 3.13 LAPAN-A3 AIS data 2018.

Figure 3.13 shows that LAPAN-A3 collects AIS data from 5-9 million AIS data and around 500000 to 700000 MMSI every month. From this statistic, it is shown that LAPAN-A3 receives less AIS signal compare with LAPAN-A2. However, since it is a global cover area, LAPAN-A3 could detect MMSI better than the LAPAN-A2 satellite.

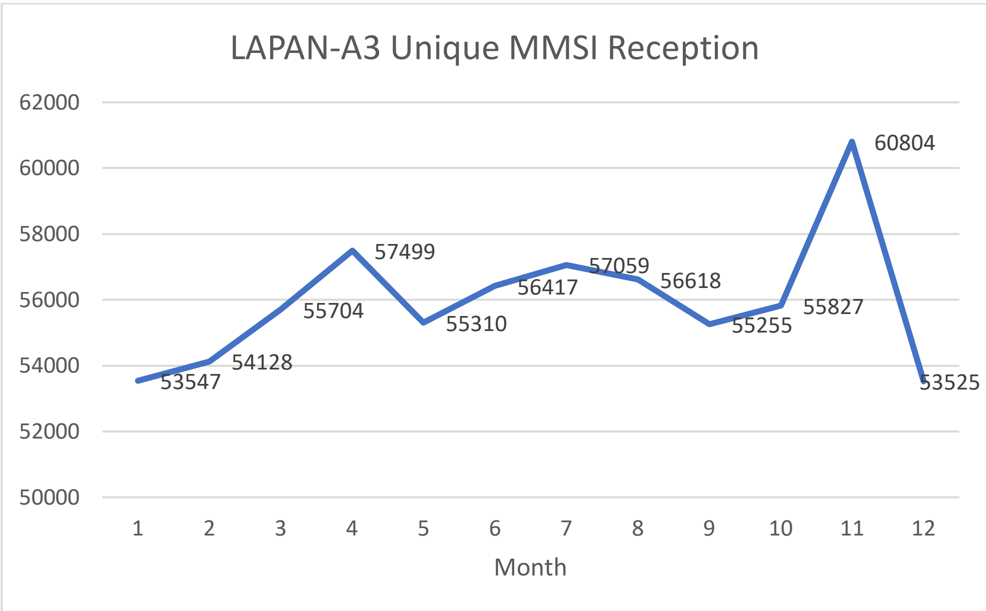

Figure 3.14 LAPAN-A3 unique MMSI reception (2018).

LAPAN-A3 also could detect more distinct or unique MMSI ships around the globe compare with LAPAN-A2 Satellite. In 2018, it is shown that the distinct ship varies every month, as in Figure 3.14.

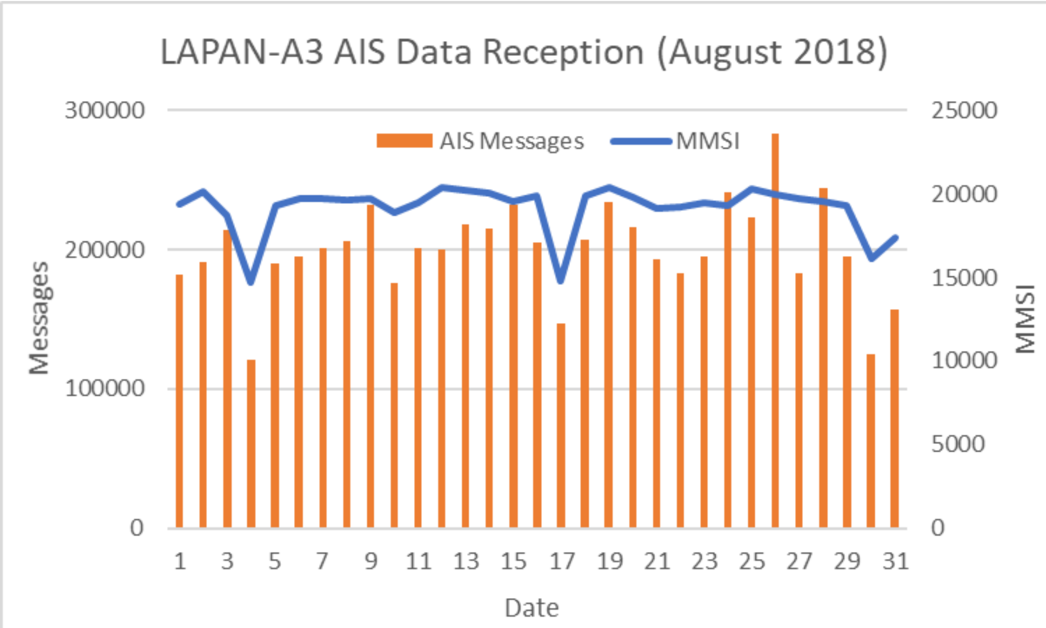

Figure 3.15 LAPAN-A3 data reception daily. (August 2018)

Figure 3.15 shows that the LAPAN-A3 satellite received AIS messages between 120000 to 230000 messages and also 15000 to 22000 MMSI identifiers per day. Compare with LAPAN-A2; then the messages data reception is less; however, it gets about 15% more MMSI identifiers.

3.3.4 Combination of LAPAN AIS Satellite

Since LAPAN-A2 and LAPAN-A3 having a different orbit, the typical ground track is as in Figure 3.16. Based on each satellite's orbital characteristic, it could calculate that the radius of the coverage area of the LAPAN-A2 satellite is 2750 Km, and LAPAN-A3 is 2483 Km.

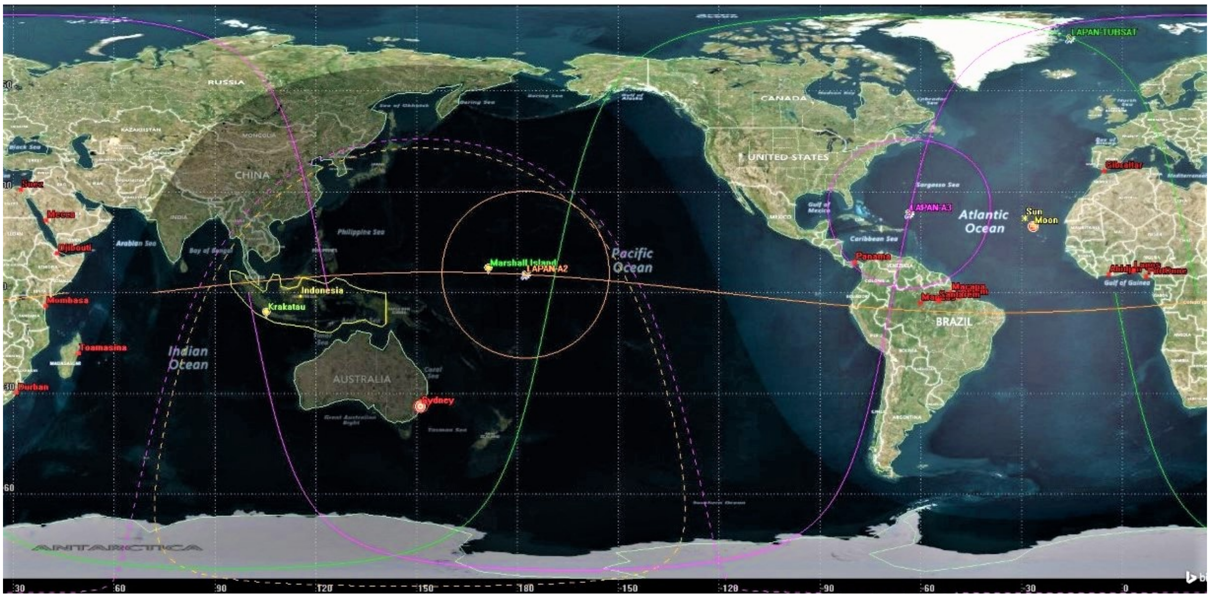

Figure 3.16 LAPAN-A2 and LAPAN-A3 orbit.

The different altitude of each satellite also impacts a different number of the message received by satellite. During that satellite's operation, the AIS data from these two satellites combined for having overall AIS in the world. The low and near-equatorial orbit inclinations allow satellites to pass through Indonesian territory 14 times per day, while polar orbit gives global coverage.

Table 3.3 AIS Reception Parameter of LAPAN Satellites

Parameter (Daily)	LAPAN-A2	LAPAN-A3
Average	464818 ± 9%	192536 ± 11%
Distinct MMSI/Ships	16030 ± 5%	24297 ± 5%

Table 3.3, shows that LAPAN-A2 gets two times larger AIS data messages to compare with LAPAN-A3. However, LAPAN-A3 collecting about 1.5 times more MMSI than LAPAN-A2. By making a comparison with AISSat-1, which carries a similar receiver, then the detection performance of the LAPAN-A2 satellite is comparable, especially before AISSat-1 got the software updated [59].

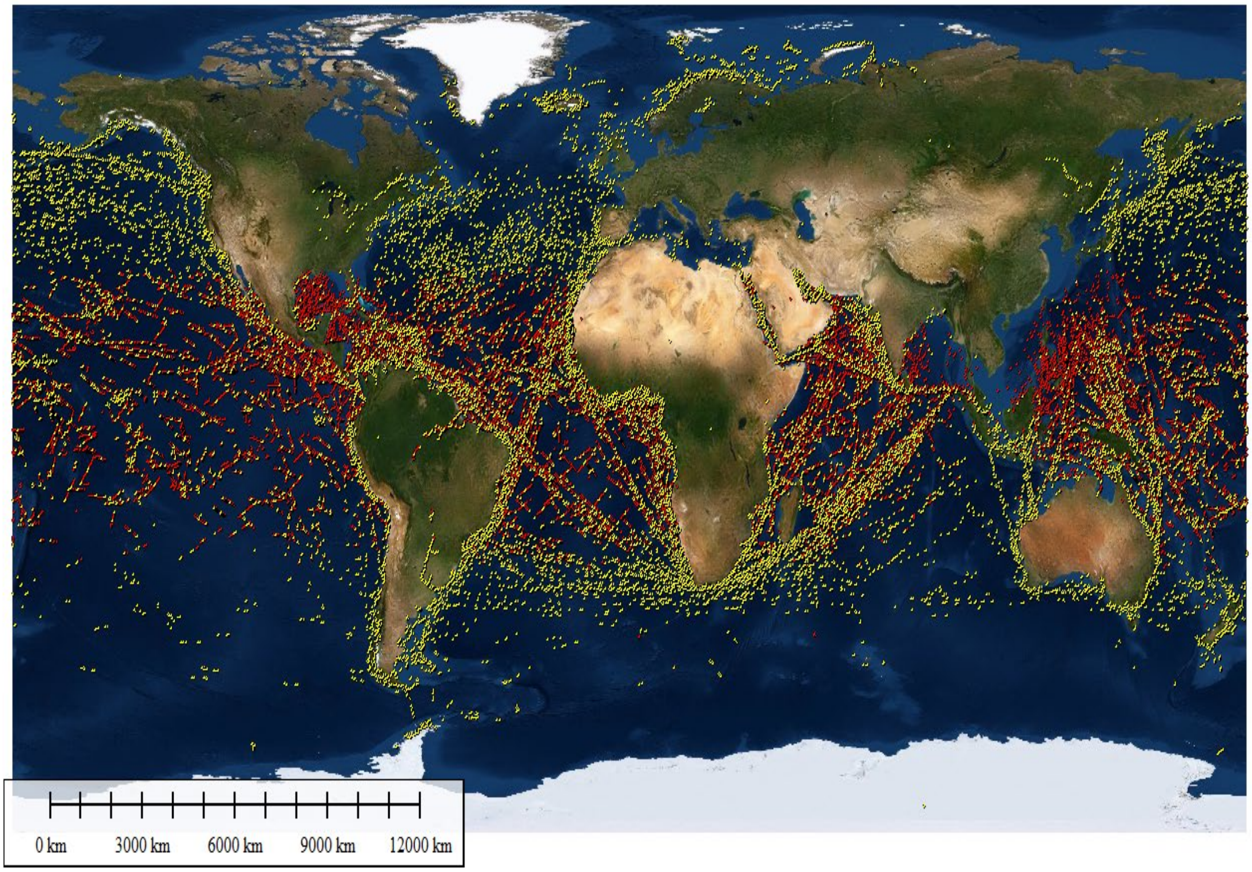

Figure 3.17 LAPAN-A2 and LAPAN-A3 combined AIS data.

To show AIS data and images in this thesis, Global Mapper, a GIS software, is used. Figure 3.17 shows the AIS data combination detected by both LAPAN-A2 and LAPAN-A3 satellite on 18 March 2018 for 24 hours. LAPAN-A2 detected 416396 AIS messages (red dots), and LAPAN-A3 detected 253879 AIS messages (yellow dots). From the figure, it also shows the global distribution of ships.

The data also shows that MMSI received from LAPAN-A2 is smaller than the LAPAN-A3 satellite. The reason why the MMSI of LAPAN-A2 is less than LAPAN-A3 due to its orbital characteristic, which serves the only equatorial region. Hence there is no chance of LAPAN-A2 to receive an AIS signal in the north region and south region of the earth.

3.3.5 Ship Detection by LAPAN Satellites

To study LAPAN-AIS satellite reception's detection performance, a terrestrial AIS receiver mounted in the Kupang area. Kupang area is one of the eastern parts of Indonesia. This location is determined since it is on an international ship route. The number of distinct ships in the AIS data can be found by counting the number of different MMSI numbers across all message types. Table 3.4 gives information about all of the distinct ship detected by the Kupang Terrestrial Station compare to the satellite detection. Based on the table, it shows that LAPAN-A2 could detect between 31-42% AIS data, and LAPAN-A3 could detect 25-29% AIS data compare with terrestrial receiver [58].

Table 3.4 Comparison of LAPAN AIS Data to Terrestrial AIS Receiver [58]

Date: 7 August 2018			Date: 8 August 2018		
LAPAN-A2	LAPAN-A3	Terrestrial Station	LAPAN-A2	LAPAN-A3	Terrestrial Station
525001120	219483000	219483000	210246000	525006037	210246000
525006037	503002000	374216000	432919000	525100417	235009760
563053800	525005009	503002000	525100417	525105003	241276000
563771000	525006037	525001120	525105003	525200077	308579000
563860000		525005009	525200077		432919000
636015641		525006037			477139700
		525016204			477351900
		525022177			525001090
		525119033			525006037
		563053800			525025056
		563771000			525100417
		563860000			525101060
		636015641			525105003
		636016460			525200077
					563053800
					636016460

Besides installing a terrestrial AIS receiver in the Kupang area, the comparison has also been made with AIS data from an AIS data provider, PT. Imani Prima. This company is one of Orbcomm satellite AIS data distributors and several terrestrial AIS data sources in Indonesia. The company provides a 4.665.842 AIS data combination of terrestrial and Orbcomm AIS satellite fleet. This data-filtered specifically around Indonesia and compared with the result from 663.846 data from LAPAN-A2 and LAPAN-A3 AIS data simultaneously on 16 March 2018, 00:49:43 UTC to 23:21:19 UTC. Figure 3.18 shows a combination of LAPAN-A2 and LAPAN-A3 AIS data. Figure 3.19 shows the combination of those LAPAN AIS satellite's data and the provider data sources (green dot).

By extracting only the AIS message from LAPAN-A2 and LAPAN-A3 that could not be found in the AIS data from that provider, LAPAN-A2, and LAPAN-A3 could detect 4.22% new AIS data. Even though the total data from those satellites is only 14,2% compared with the provider data sources, this result shows that, even with several satellites and terrestrial receiver combination from the data provider, LAPAN satellites could detect new AIS data that might not be detected by other satellites or terrestrial AIS.

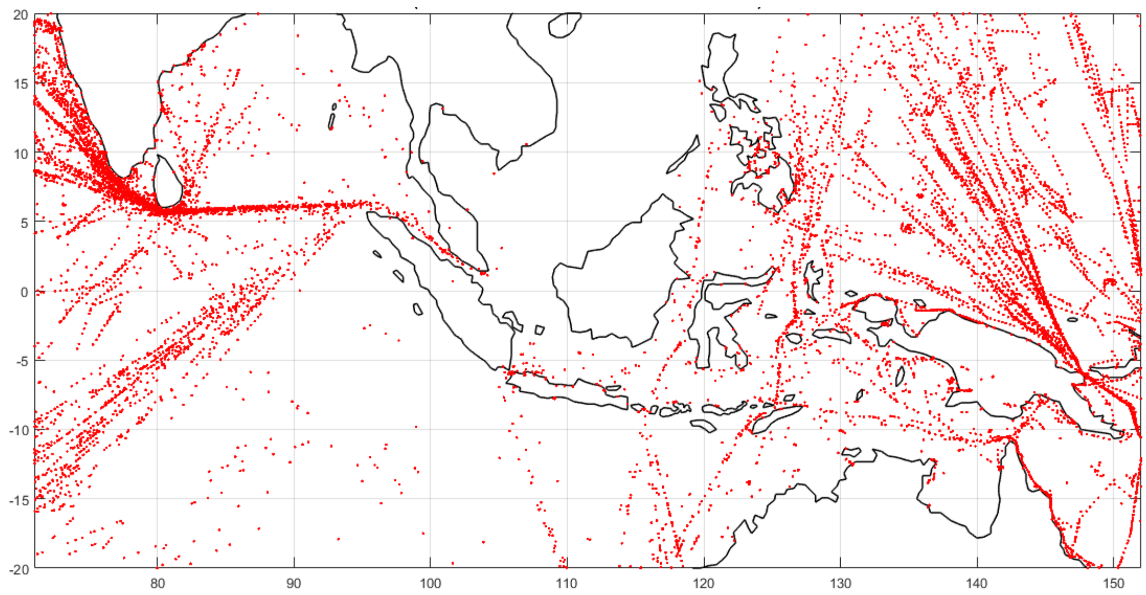

Figure 3.18 AIS messages of LAPAN-A2 and LAPAN-A3 combination on 16 March 2018.

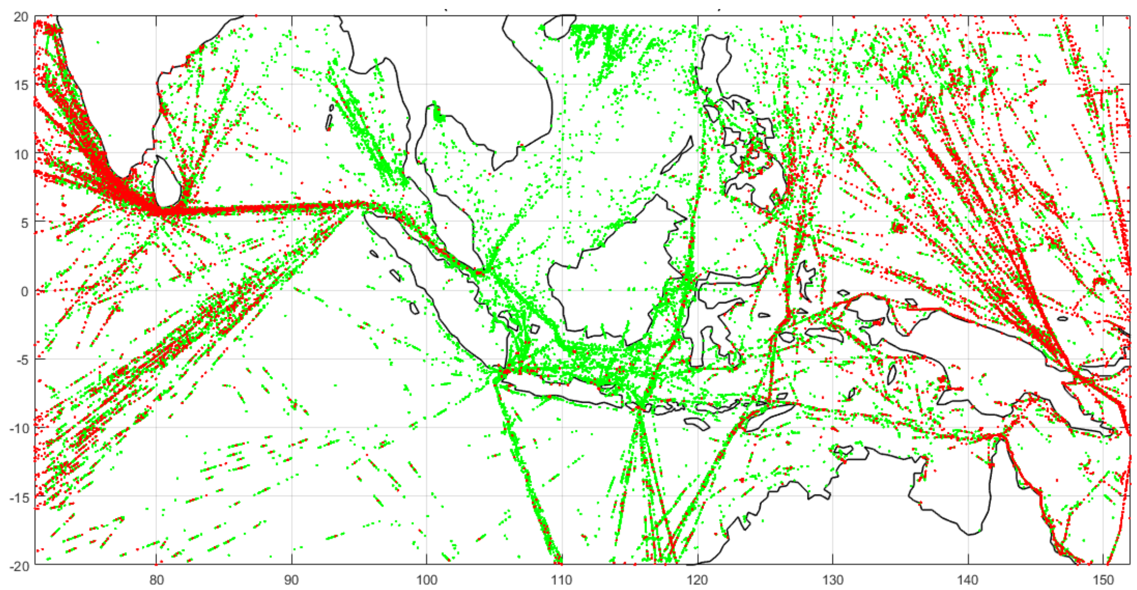

Figure 3.19 Combination of AIS messages of LAPAN-A2, LAPAN-A3, and the AIS data provider on 16 March 2018.

As seen in Figure 3.19, LAPAN-A2 and LAPAN-A3 satellites detected less AIS data in most areas surrounding Malaka Straits and the South China sea. In the Malaka strait, Java sea, and Makassar Strait, most of the AIS data covered by terrestrial AIS so that it could cover a lot of ship information. However, the AIS detection by LAPAN-A2 and LAPAN-A3 increasingly better in the Pacific Ocean, the east coast of Australia, and south of the India sea.

3.4 Several Maritime Cases Identified by AIS from LAPAN-Satellites

During the operation of LAPAN-A2 and LAPAN-A3 Satellites for maritime surveillance, its AIS data has been used by Indonesian authority to identify and also to investigate several cases in Indonesia. This section describes several maritime cases that get public attention, especially in Indonesia.

3.4.1 Brahma-12 Tug Boat Crew Kidnapped

In March 2016, there was a report on Indonesian-registered tug boat Brahma-12 MMSI 525024320 towing a barge, Anand-12 loaded with 7,000 metric tons of coal, departed Kalimantan, Indonesia for a power plant in Batangas, Philippines. Based on the report, 17 perpetrators armed with firearms boarded the tug boat from one grey speed boat powered by three outboard engines and one wooden-type motorized pump boat propelled by a built-in double engine. The perpetrators forcibly abducted all its 10 Indonesian crew and abandoned the tug boat [60]. The tug boat's missing became public news in Indonesia since the perpetrators requested a ransom to release the crew [61].

LAPAN-A2 satellite received the tug boat AIS data from 1 January to 29 March 2016 (when first news released) and showed that the last AIS transmitted by the boat happen on 25 March 2016 at 14:00:12 UTC, as in Figure 3.20. The last position of the boat received by LAPAN-A2 is located on Latitude 5.1214700 and Longitude 119.6399994. This last signal indicated that the AIS transmitter was switch off by the perpetrators. This satellite information was then released to the Indonesian maritime authority. This boat's tracking could be done only by the LAPAN-A2 satellite since LAPAN-A3 was launched after this case happened.

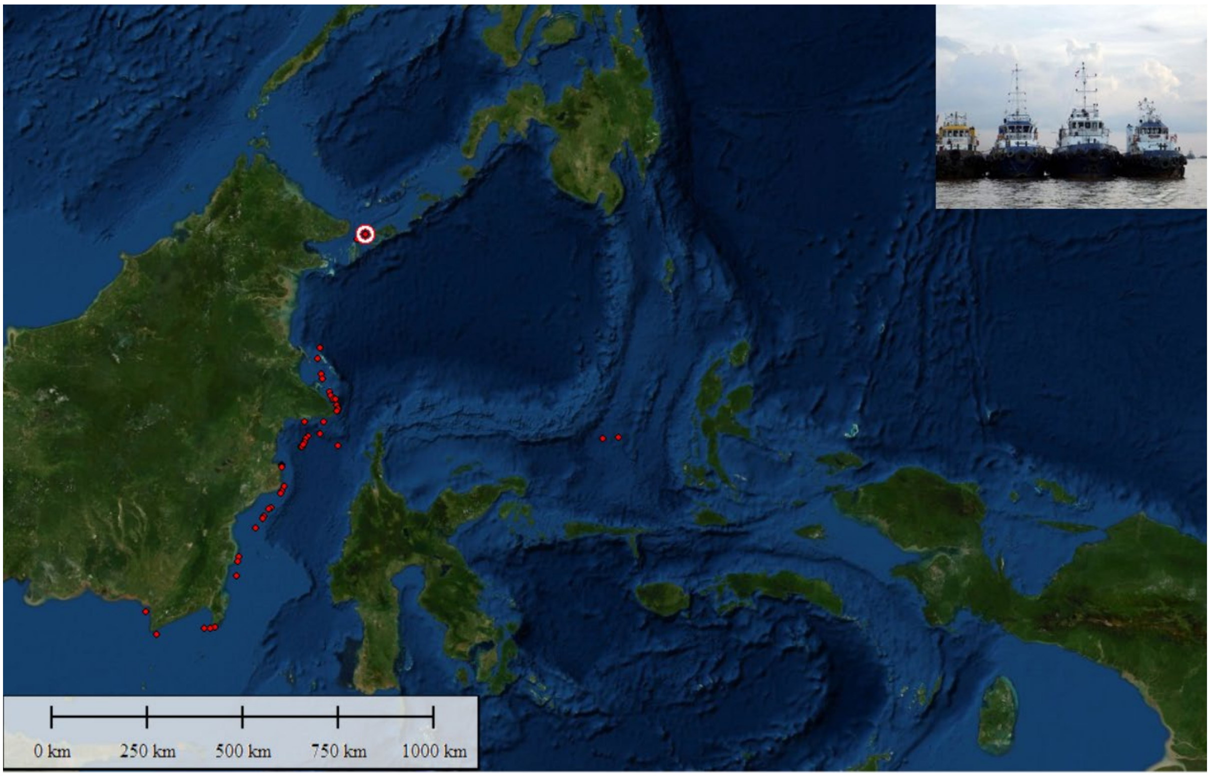

Figure 3.20 Brahma-12 tug boat AIS information before crew kidnapped. (*ship photo by Husni via www.vesselfinder*)

3.4.2 *Case of Coral Reef Damaging by Cruise Ship*

On 4 March 2017, there was a cruise ship named Caledonian Sky with MMSI 311061100 running aground during low tide and damaging around 1600 square meter protected coral reef area [62]. This incident becomes an international issue since the damaging area and the coral might difficult to be repaired anymore. According to the AIS data from 1 January through 30 March 2017, detected from LAPAN-A2 and LAPAN-A3 satellites, this ship was underway from New Zealand and continue to Papua New Guinea and entering Indonesia ocean and later hit the coral reef and then the ship continues to the Philippines.

Figure 3.21 also shows a good AIS combination detection from LAPAN-A2 and LAPAN-A3 satellite. As seen, for this case, LAPAN-A3 (yellow dots) mostly covered the south area, and LAPAN-A2 mostly could detect the AIS of the ships in the equatorial region (red dots). Those data were then combined for tracking analysis of the targeted ship.

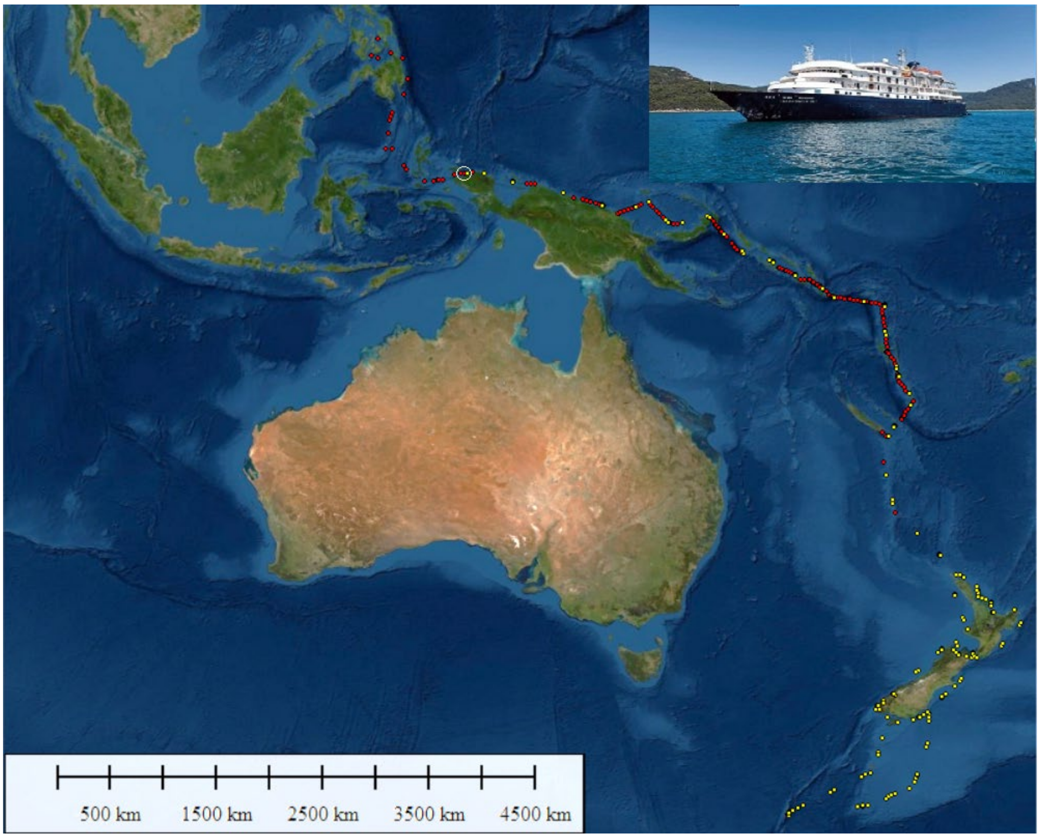

Figure 3.21 Caledonian Sky Travel from 1 January through 30 March 2017 (Grey circle; the Coral reef area hit by the ship)(*ship photo by Joshua Angles via* www.vesselfinder.com)

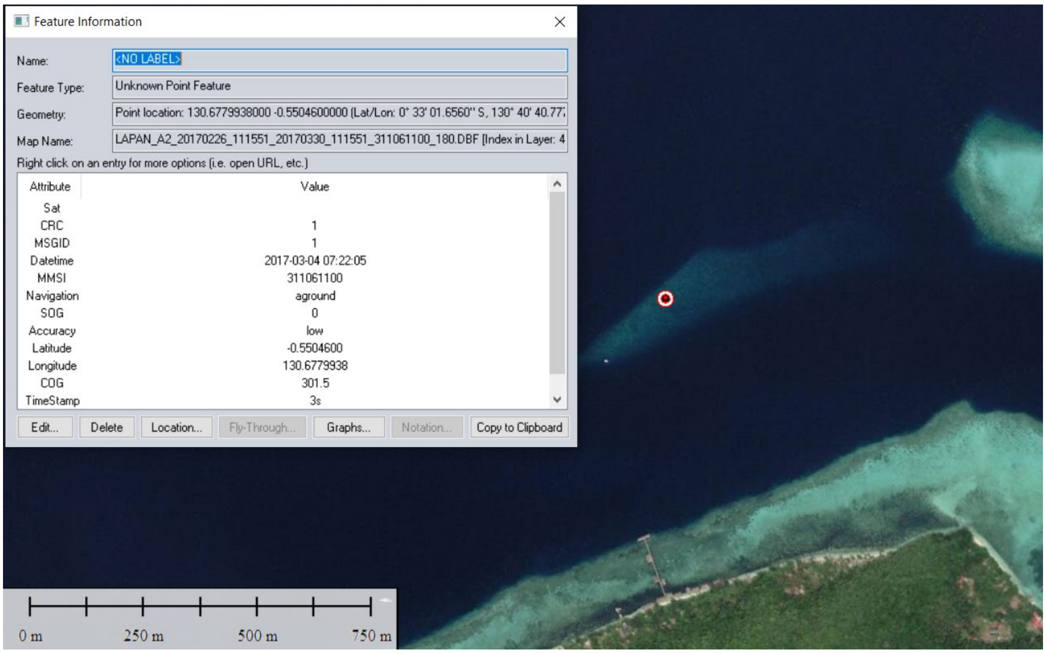

Figure 3.22 Caledonian Sky AIS messages mention "aground" in its navigation status.

Figure 3.22 shows more detailed detection of AIS information from the ship. It shows that the ship "aground" status in the coral reef area. The AIS information detected from the LAPAN-A2 satellites shows that the ship hit the coral area from 05:35:04 until 10:50:00 UTC on 4 March 2017. After the case happens, Indonesia's government requests shipowner compensation to repair the damage [63].

3.4.3 *Missing of Nickel Ore Bulk Carrier*

On 24 August 2019, LAPAN get a request from a shipowner of MV. Nur Allya, (MMSI 525020021, a bulk carrier loaded with nickel ore) to find the ship's latest position since they did not get any information from the ship from 20 August 2019. Also, on that day, they got a distress call information from that ship from Indonesia National Search & Rescue Agency (BASARNAS). By using AIS information from the LAPAN-A2 satellite, it could be found that the latest AIS information was received on 20 August 2019 at 17:04:36 UTC, as shown in Figure 3.23.

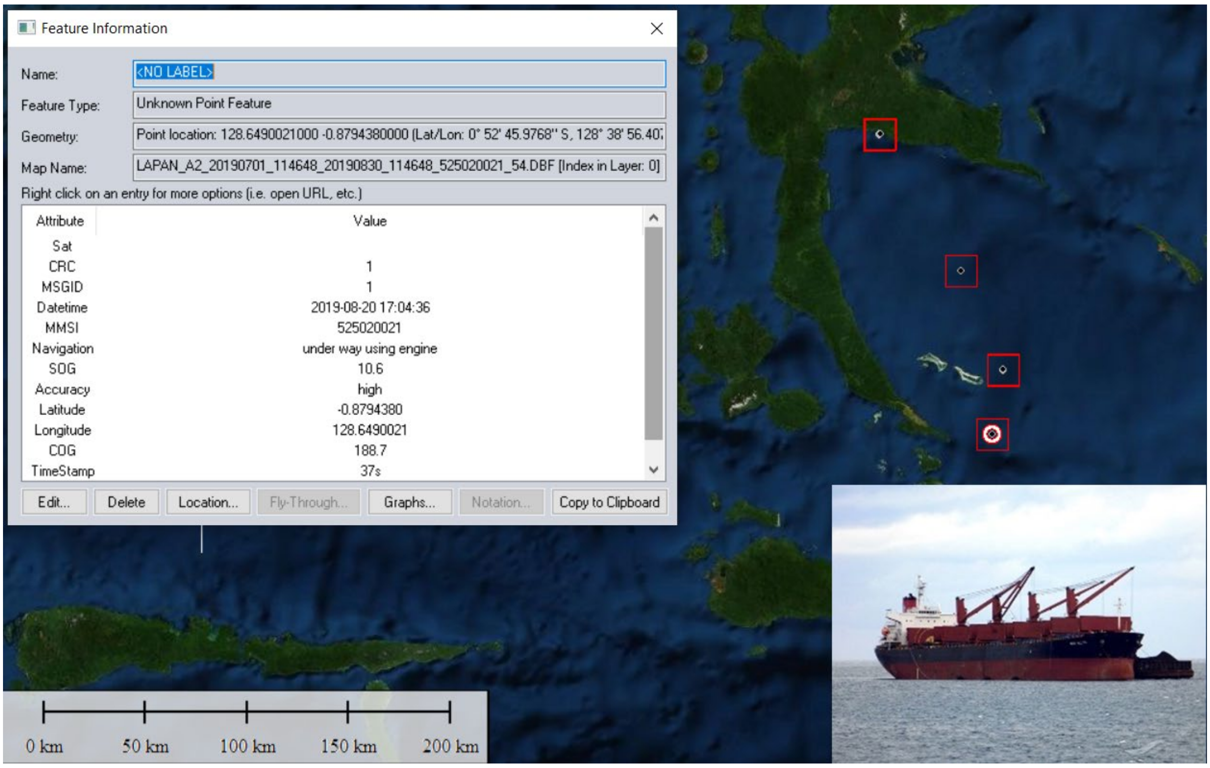

Figure 3.23 Last position of MV. Nur Allya received by LAPAN-A2 Satellite
(ship photo by Husni via www.vesselfinder.com)

After collecting all information, including the distress call beacon from the ship that keeps on transmitted that found about 171 Km from the last AIS signal, several attempts to find the ship visually from LAPAN-A2 and LAPAN-A3 has been executed as in Figure 3.24.

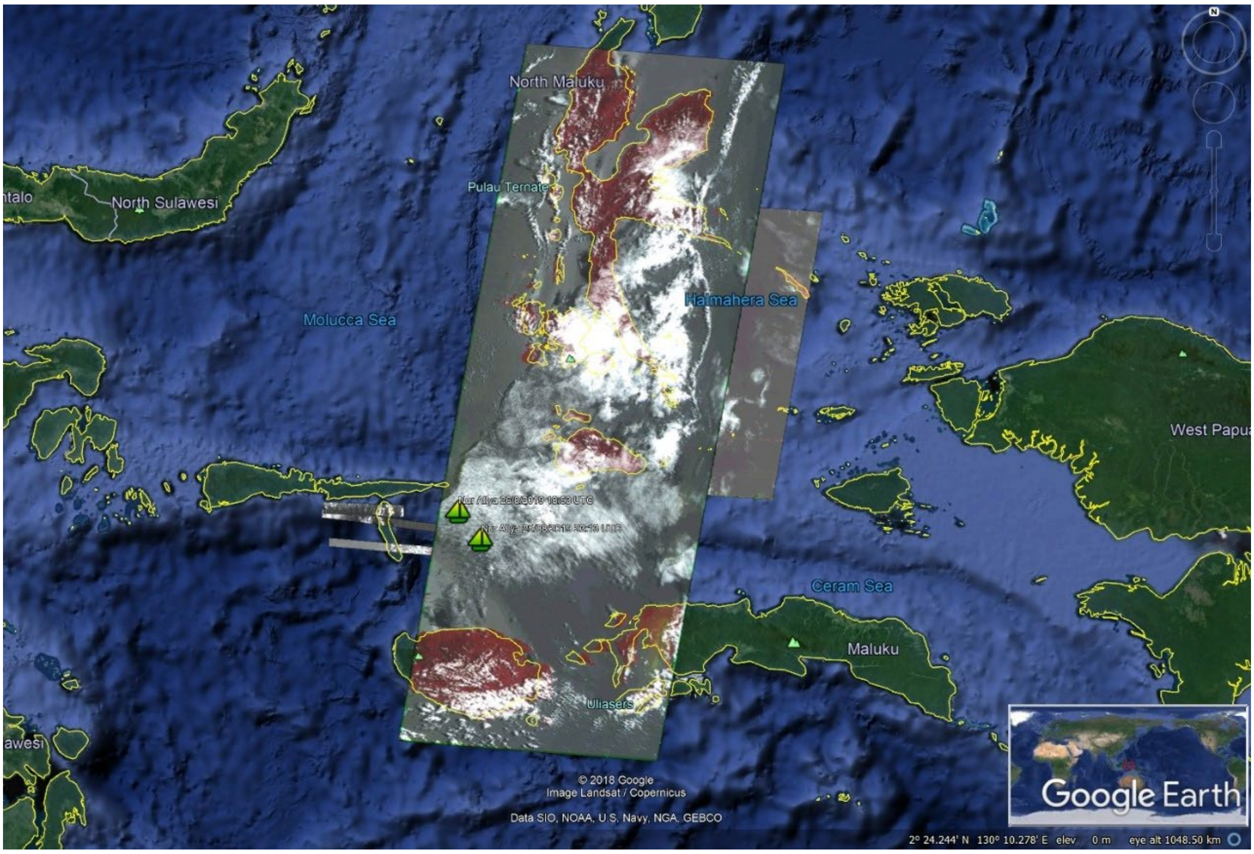

Figure 3.24 Imaging of the area of the missing carrier.

The shipowner also used the information analyzed from satellite imaging to request the rescue boat and plane to check the suspect location visually. However, after several days of imaging from 24-26 August 2019, the specific target could not be found. For several months the ship declared missing [64], and, by using the ocean pinger locator, the carrier declares sinking and fears that all 25 crews could not escape from the sinking vessel [65].

3.5 Typical Potential Illegal Activity Detected by AIS from LAPAN-Satellites

Several typical potential illegal activities described in this section, i.e., single MMSI used by several vessels, potential transshipment behavior, and also spoofing of AIS information. These typical potential illegal activities are usually difficult to be detected by the terrestrial AIS system. So, by using the AIS detection from the satellite, this behavior could be detected.

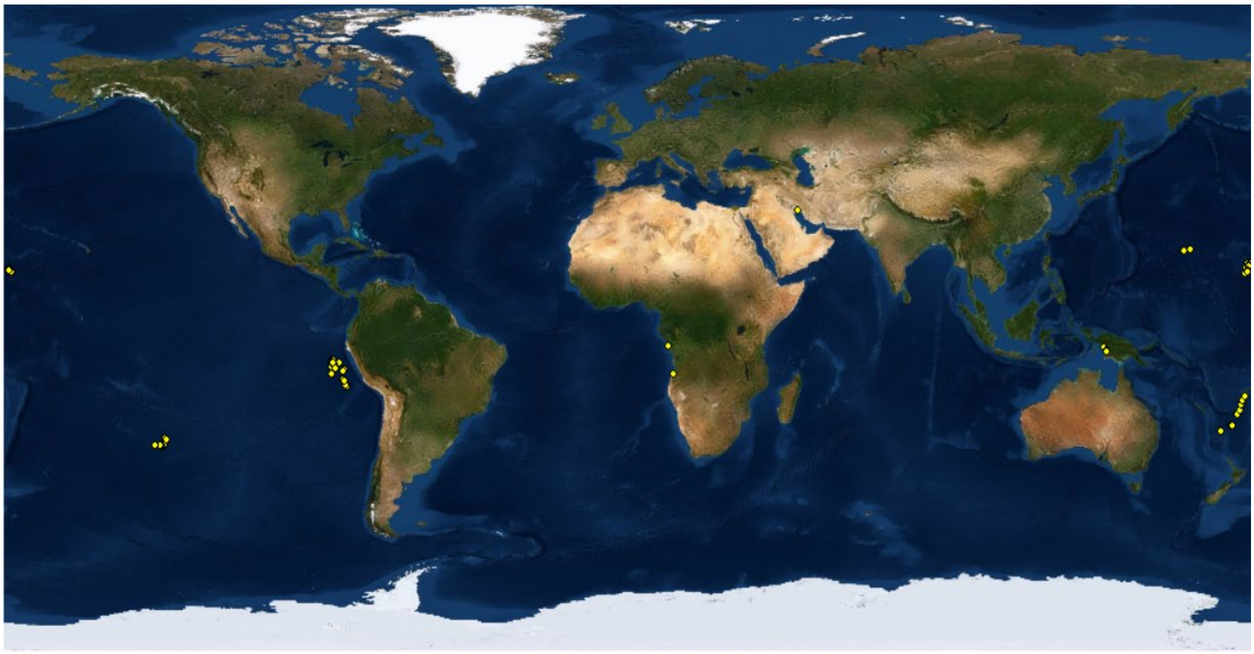

Figure 3.25 Single MMSI was used by multiple ships (yellow dots).

AIS system in LAPAN satellite also could identify usage of the same MMSI by multiple ships. The usage of the same MMSI for different ships signifies suspicious illegal activity in the ocean. This means that throughout the oceans, multiple vessels are simultaneously broadcasting the same MMSI number, making them difficult to be distinguished from one another without closer inspection [66]. LAPAN-A3 detects 266 AIS signal using the same MMSI of 412000000 within the 15 days from 1-15 May 2019, as in Figure 3.25, that spread from the Pacific Ocean, Arafura Ocean-Indonesia, and South Africa. This is one of the advantages of using AIS based satellite since it could acknowledge the MMSI usage in a different location.

Transshipment is another case of Illegal activities in the ocean. The transshipment is an exchange of cargo between two ships in the middle of the ocean. This transshipment usually happens into an encounter as likely rendezvous and loitering event as potential rendezvous. Encounter is an activity interaction between two vessels that remained within 500 meters of each other for longer than 3 hours while traveling at less than 2 knots. This event is mostly challenging to be identified since usually one of the ships turn off its AIS transmitter. A loitering event happens when a ship moves less than 2 knots for longer than 8 hours [67].

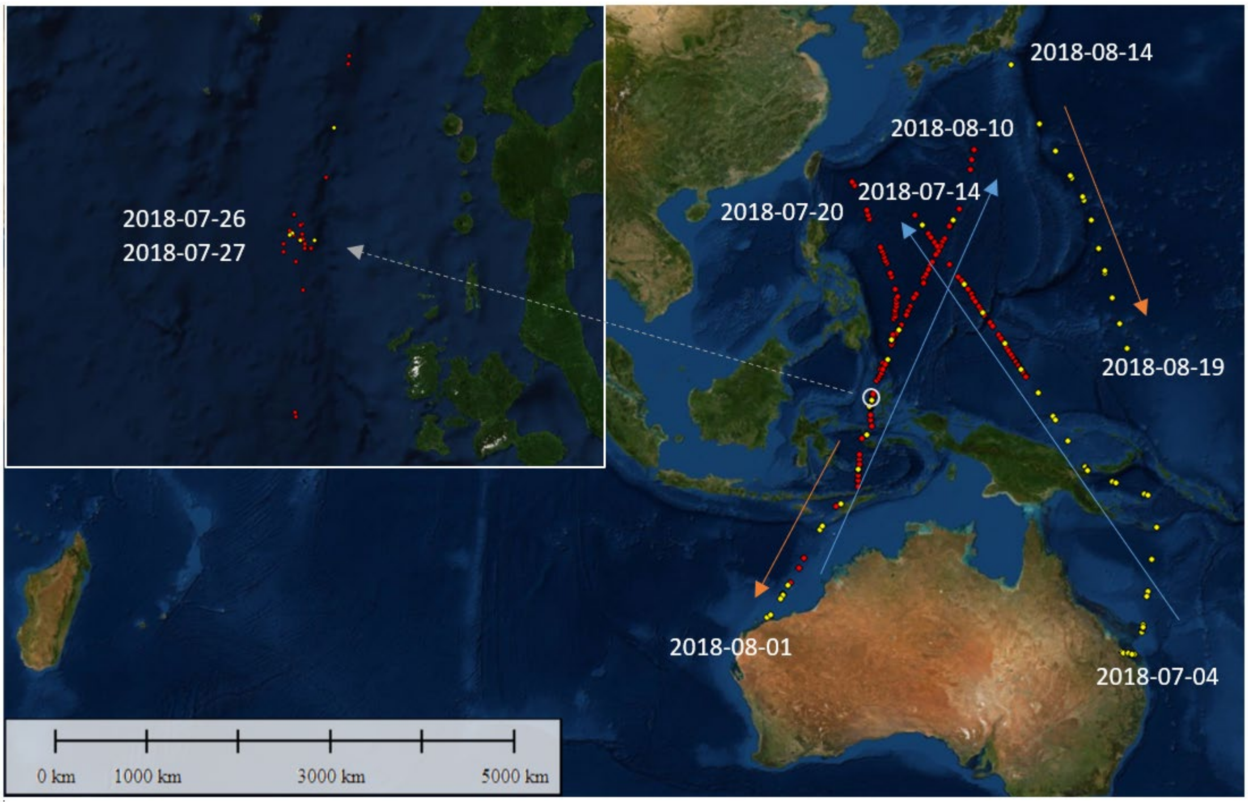

Figure 3.26 Loitering events of LNG Tanker in the Indonesian ocean.

Figure 3.26 shows a tracking activity of a liquid gas tanker with a Greece flag that traveled to and from Australia by using the international sea lane and Archipelagic sea lanes in Indonesia. By combining LAPAN-A2 and LAPAN-A3 satellites, there was a loitering event that happens from 26-07-2018 at 06:57:33 UTC till 27-07-2018 21:23:42 UTC that this tanker ship slowdown below 2 knots for more than 8 hours and also around 50 Km from the nearest island. By looking at the ship's track from 04-07-2018 to 19-08-2018, this loitering only happens once, and this becomes one of potential rendezvous, which tends to lead that a transshipment may happen during that period. This typical potential illegal activity surveillance in the open ocean only could be done by using satellite monitoring.

Another case of the strange behavior of ships could be seen below in Figure 3.27. This figure shows several ships located in the land or desert on the African continent from 1 to 31 January 2020. One can see a fishing vessel under a Chinese flag located in the desert in the inset. From the AIS data, this fishing vessel use class B of AIS transmitter. Besides this fishing vessel, some bulk was carried reported in the desert based on its AIS data.

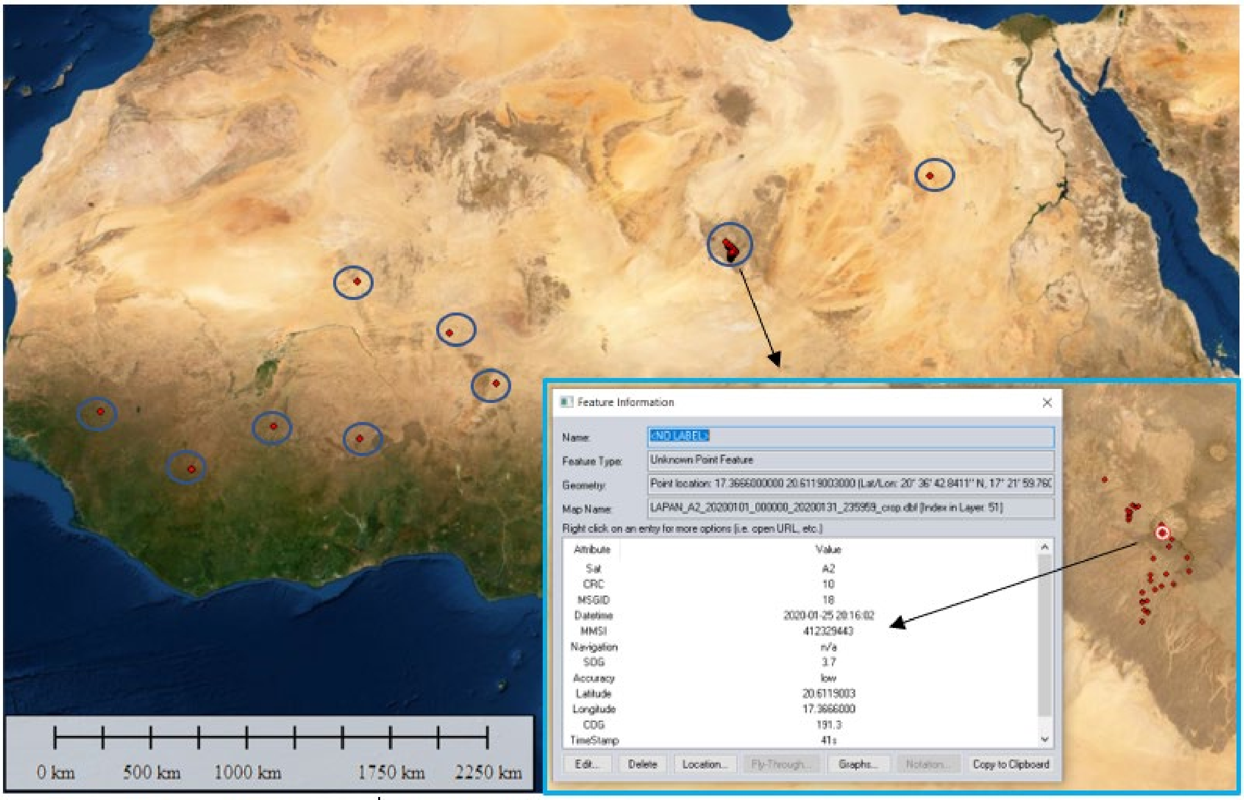

Figure 3.27 Ships located in land/desert.

This strange information usually happens because either the AIS transponder has malfunctioned, the data got scrambled in transmission, or the system has tampered so that the ship reports a false location to hide its valid location [68]. This false reporting usually implemented by the fishing vessel. Another explanation is a spoofing event happen that shows several instances of multiple vessels reporting their locations as being on land. The ship's spoofing activity that causing several ships located in not real locations reported to happen in the Black sea [69]. The spoofing also reported happening latest in Chinese port [70]. The latest spoofing report in Shanghai showed ships jumping every few minutes to different locations on rings on the Huangpu's eastern bank. The ships appeared to congregate in large circles by visualizing the data spanning days and weeks [71].

4

Discussion of Problem Areas; Saturation in Certain Areas

The previous section has discussed that space-borne AIS satellite deployment has its challenges because AIS is primarily intended for sea-level reception and communication.

One significant issue for space-based AIS is the self-organization characteristic of the terrestrial AIS communication system. All messages exchanged from ships within the 30-40 nm VHF range are synchronized, meaning that none of the AIS reports are sent at the same frequency at the same time. It guarantees the operation of the application without any message failure. AIS receiver mounted in the satellite, however, sees some of these self-organizing cells within its footprint (> 3000 km in diameter). Because there is no synchronization between the cells, the satellite may receive AIS messages at the same frequency from different vessels simultaneously. In this case, a message collision can occur and lead to the loss of message [72].

The phenomenon of message collision or interference disturbance is also faced by the AIS system in LAPAN-A3 and LAPAN-A2 satellites. Since the receiver in those satellites using onboard processing, all AIS signal coming from the ships is processed directly in space. As described in the previous chapter, there are typically two AIS processing techniques, either onboard processing or on-ground processing. Both techniques have different advantages. The onboard processing has the advantage of faster processing; however, it might have limited from the satellite resources compared to the on-ground processing, which may be time-consuming but could be processed with a more complex processing technique.

Collision and interference in AIS data could be seen in AIS data from LAPAN-A2 and LAPAN-A3. The AIS data from both satellites have a CRC identifier to verify the AIS's integrity data flow from the ships to the satellite and satellite to the ground station, as described in Table 3.2 in the previous section.

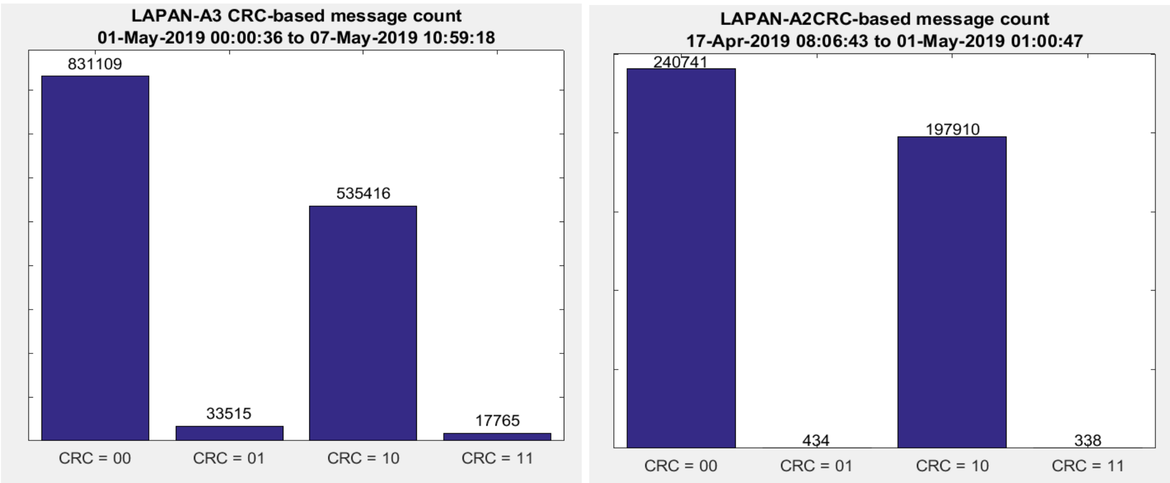

Figure 4.1 LAPAN-A2 and LAPAN-A3 typical data integrity.

Figure 4.1 shows that LAPAN-A3 AIS data validity is 37,8%, and LAPAN-A2 AIS data validity is 45 % of AIS satellites' total data. It also shows that most of the invalid AIS data happen due to invalid AIS data from the ship received by satellite. This means that the AIS signal transmitted by ships might get collision or interference from another source of the disturbance. The above figure shows that the AIS receiver's performance in LAPAN-A2 better than the LAPAN-A3 satellite, even the receiver onboard and its omnidirectional antenna, is identical. LAPAN-A3 also covers all the ocean, so it has a chance to face more data collisions than LAPAN-A2 satellites.

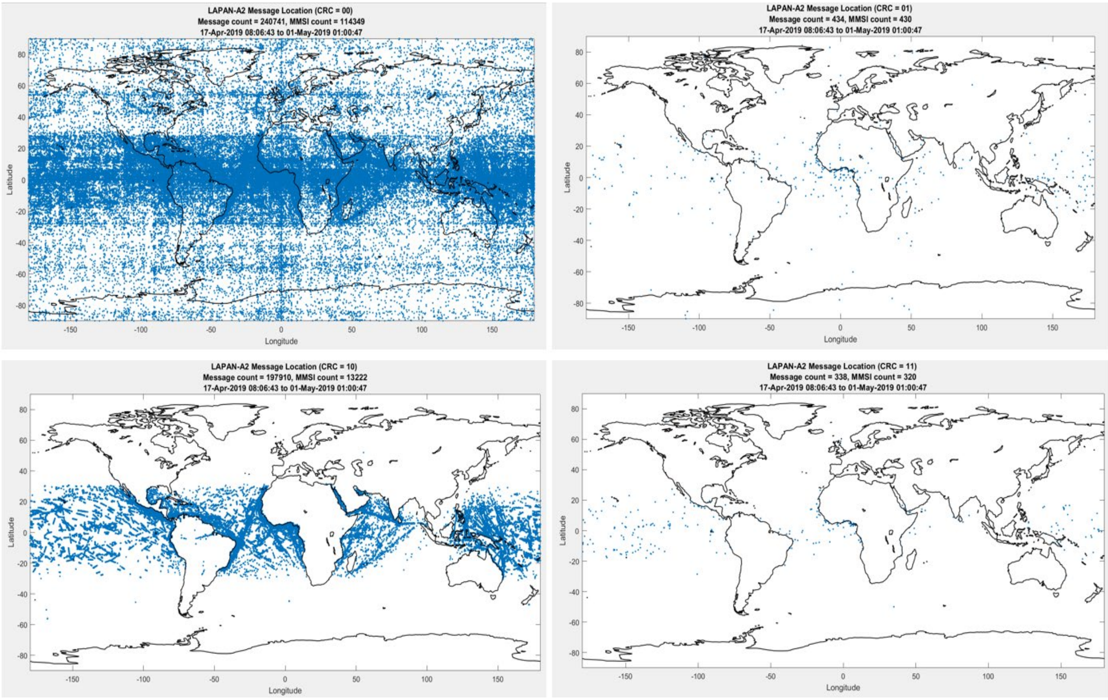

Figure 4.2 LAPAN-A2 AIS data distribution from each CRC type.

As in Figure 4.2, CRC ‘00’ creates the most substantial wrong AIS information spread around the world even though the satellite orbiting only in the equatorial region. For CRC 01 and 11, it could be seen that the invalid AIS information is less compared with other CRC.

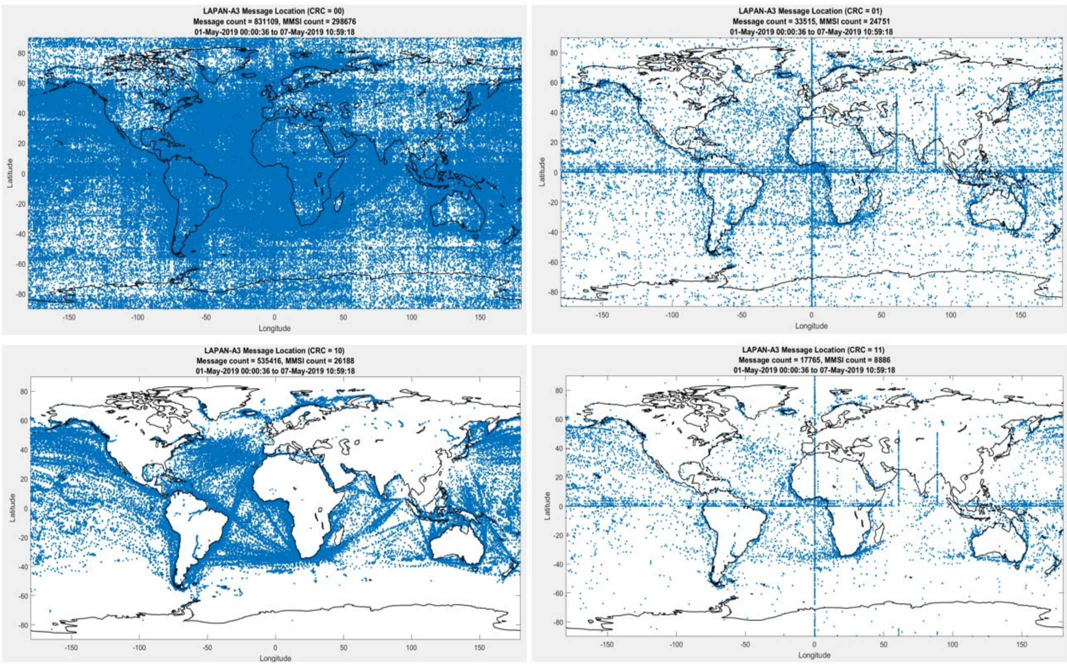

Figure 4.3 LAPAN-A3 AIS data distribution from each CRC.

In Figure 4.3 also, there is much wrong AIS information due to invalid CRC. Those figures show that most of the invalid CRC happen in the ship's position feature in AIS information.

The satellite AIS sensor's saturation due to the high number of messages mainly happens in high-density traffic areas such as the Mediterranean or the Baltic Sea. Message collision and receiver saturation are the main factors impacting the performance, measured as the Probability of Detection (PoD) of picking up an AIS position report transmitted by an AIS carrying vessel [72].

A description of the satellite AIS difficulties was well presented in many publications [27] [30] [73] [74], in particular, in [75]. The problems briefly analyzed to obtain a common understanding of space-based AIS.

The first obvious problem that comes into effect due to the high speed of a satellite relative to the boat is the Doppler shift. At an altitude of 650 km, the usual satellite speed is around 7.5 km/s, whereas an open sea high-speed cargo vessel can sail at 20 knots (37 km/h or 0.01 km/s equally), which is a fraction of the satellite's speed and can therefore be ignored. In wide-angle antenna applications, the Doppler shift effect could be a problem, and no adaptive frequency filter presence is required as frequency shifts for the received signal are required to be carried. On the other hand, the Doppler shift property works nicely to distinguish various signals when enhanced frequency filters are used for receiver RF-frontend or signal processing. Since this Doppler shift for a 650 km LEO satellite varies within the ±3.5 kHz range, it can be selectively used to distinguish signals from different areas of relative velocity. The Doppler shift frequency range for the 60° aperture angle antenna is ±2 kHz, and the value for the 38° antenna is ±1,3 kHz. Therefore, to detect their origin and avoid message collisions, a high-performance satellite-AIS receiver should be equipped with algorithms and an RF-frontend to take advantage of different AIS frequency signals. Another solution is to use a narrow-angle antenna to minimize the risk of message collisions.

For making the identification area of the most invalid CRC happen during AIS data acquisition, a comparison between the area of AIS data acquisition could be described in the world map. In this identification, AIS data from LAPAN-A3 is chosen since it has global coverage better than the LAPAN-A2 satellite.

The data used in CRC distribution mapping is a post-report version in which all valid and invalid AIS messages are still held in one .txt formatted file. The AIS information required for CRC mapping includes CRC sign, timestamp (t), latitude (λ), and longitude (γ). For the first time, this post-report data is extracted and saved in a numeric format. The extracted information is then assigned as D that consisted of CRC, t, λ, and γ of each detected message.

$$D = \{CRC, t, \lambda, \gamma\} \tag{4. 1}$$

In order to perform the mapping, an SGP4 orbital mechanics propagator is employed to estimate the satellite footprint on Earth at a particular time. The LAPAN-A3 satellite is propagated by using the SGP4 from T_{min} to T_{max}. The T_{min} and T_{max} refer to the minimum and maximum time of propagation time range, which can be extracted from the extracted post-report data, D.

$$T_{min} = min(t) \tag{4. 2}$$

$$T_{max} = max(t) \tag{4. 3}$$

The SGP4 algorithm is carried out by using discrete propagation time, t_r. The total number of SGP4 will be called (n) is

$$n = ceil\left(\frac{T_{max} - T_{min}}{t_r}\right) \tag{4. 4}$$

The *ceil* function refers to a rounding process to the next higher integer.

For a given T_{min}, T_{max}, and t_r, the exact time set of the SGP4 algorithm called can be defined as:

$$t_{SGP4} = [T_{min}, T_{min} + t_r, t_{min} + 2t_r, \ldots, T_{max}] \tag{4. 5}$$

To begin the SGP4, define an element of t_{SGP4}time set, ${t^i}_{SGP4}$, in which $i = 1, 2, \ldots, n$. Estimate the latitude (λ^i), longitude (γ^i), and altitude (H^i), at i-th time by feeding this ${t^i}_{SGP4}$and satellite Two Line Elements TLE information to SGP4 function.

$$[\lambda^i, \gamma^i, H^i] = SGP4({t^i}_{SGP4}, TLE) \tag{4. 6}$$

Then, create a temporal data $D^i$to hold the D having a specific range of timestamp as defined below:

$$D^i = D({t^i}_{SGP4} - (t_r/2) \leq t \leq {t^i}_{SGP4} + (t_r/2) \tag{4. 7}$$

Next, calculate the range of satellite footprint radius (Q^i) from its center point $(\lambda^i$,$\gamma^i)$ at an altitude H^i by using the equation:

$$Q^i = \sqrt{(2.R.H^i) + (H^i)^2} \tag{4. 8}$$

R is the Earth radius constant (6378.1 km).

The next step is dedicated to including only D^imessages located on the satellite visibility area, as illustrated in Figure 4.4. Therefore, the distance of each data points of $D^i$to the center point (λ^i,γ^i) resulted from (4.6) must be calculated. Suppose the data D^iconsisted of N total messages, hence:

$$D^i = [d^1, d^2, \dots, d^N] \tag{4. 9}$$

the d denotes a particular AIS message that also consisted of CRC, t, λ, γ. If each d is indexed by k symbol, then the distance between (λ^k, γ^k) of d^k to the center point of satellite footprint (λ^i,γ^i) can be calculated using:

$$\sigma^k = 2R\, sin^{-1}\left(\sqrt{(\Delta\lambda/2)^2 + cos\lambda^i\, cos\,\lambda\, sin(\Delta\gamma/2)^2}\right) \tag{4. 10}$$

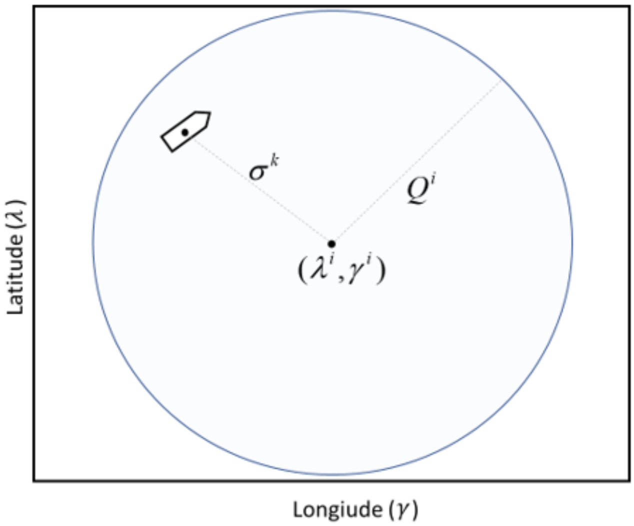

Figure 4.4. Illustration of data filtering based-on satellite field of view.

If $\sigma^k > Q^i$then the correspondent d^k will be excluded from D^i, or in the mathematical formula, this condition can be written as:

$$D^{i\prime} = D^i(\sigma^k > Q^i), \text{for } k = 1,2,\dots,N \tag{4. 11}$$

The $D^{i\prime}$is the new form of D^i in which a satellite field of view covers all of its locations.

The final step is counting on every single filtered i-th data $(D^{i\prime})$ based on their CRC sign. Since there are four types of CRC sign, the total count of them, respectively, can be expressed by:

$$N_{00}^i = D^{i\prime}(CRC = 00) \tag{4. 12}$$

$$N_{01}^i = D^{i\prime}(CRC = 01) \tag{4. 13}$$

$$N_{10}^i = D^{i\prime}(CRC = 10) \tag{4. 14}$$

$$N_{11}^i = D^{i\prime}(CRC = 11) \tag{4. 15}$$

Furthermore, in percentage, it can be expressed as :

$$N_{00}^{i}\% = \frac{N_{00}^{i}}{N_{00}^{i}+N_{01}^{i}+N_{10}^{i}+N_{11}^{i}} \tag{4. 16}$$

$$N_{00}^{i}\% = \frac{N_{01}^{i}}{N_{00}^{i}+N_{01}^{i}+N_{10}^{i}+N_{11}^{i}} \tag{4. 17}$$

$$N_{10}^{i}\% = \frac{N_{10}^{i}}{N_{00}^{i}+N_{01}^{i}+N_{10}^{i}+N_{11}^{i}} \tag{4. 18}$$

$$N_{11}^{i}\% = \frac{N_{11}^{i}}{N_{00}^{i}+N_{01}^{i}+N_{10}^{i}+N_{11}^{i}} \tag{4. 19}$$

The N_{00}^{i}, N_{01}^{i}, N_{10}^{i}, and N_{11}^{i}, respectively, are the total number of messages on $D^{i\prime}$signed by 00, 01, 10, and 11 CRC sign.

These counted messages are then assigned into several classes based on their values. The rule to classifying these counted messages is provided in Table 4.1 below:

Table 4.1 Class of counted messages

No.	**Counted messages**	**Class Number**
1	1 - 4	1
2	5 - 15	2
3	16 - 40	3
4	41 - 100	4
5	101 - 190	5
6	191 - 250	6
7	251 - 350	7
8	351 - higher	8

The same data of AIS messages from 1-7 May 2019 from LAPAN-A3 is used for this identification. The identification was used by collecting AIS messages every 60-second orbit of the LAPAN-A3 satellite. Figure 4.5 shows the percentage of valid AIS messages every 60 seconds from the satellite view. The result could be seen in Figure 4.5 as follows:

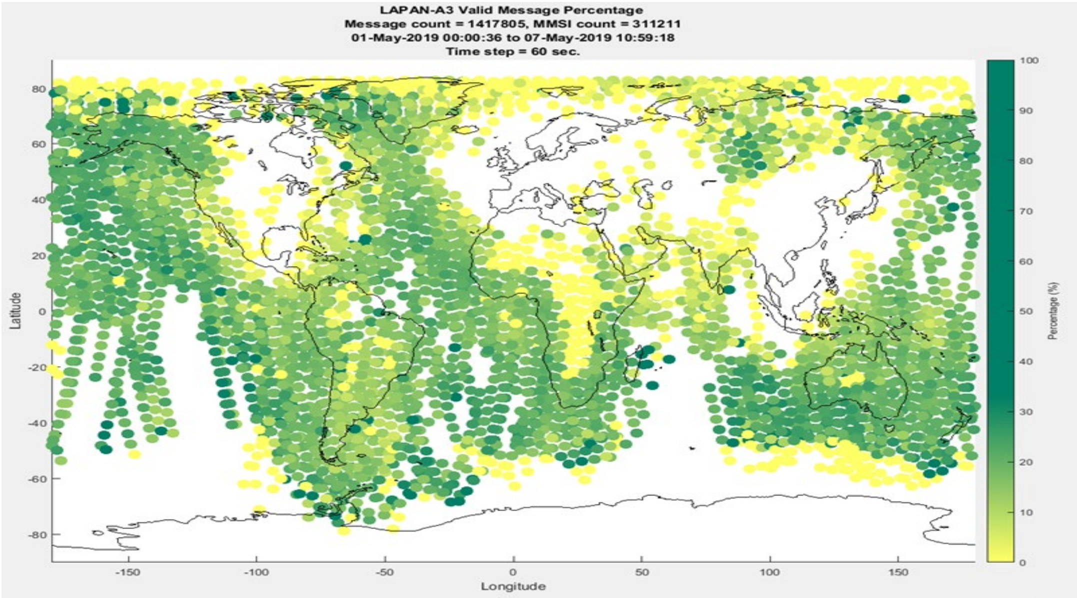

Figure 4.5 LAPAN-A3 valid AIS message distribution from orbit.

The map of valid AIS message distribution shows that several areas get less disturbance and could detect AIS data with higher validity percentages. The area with high validity AIS reception such as the south Indian ocean, south Atlantic ocean, pacific ocean, and bearing sea.

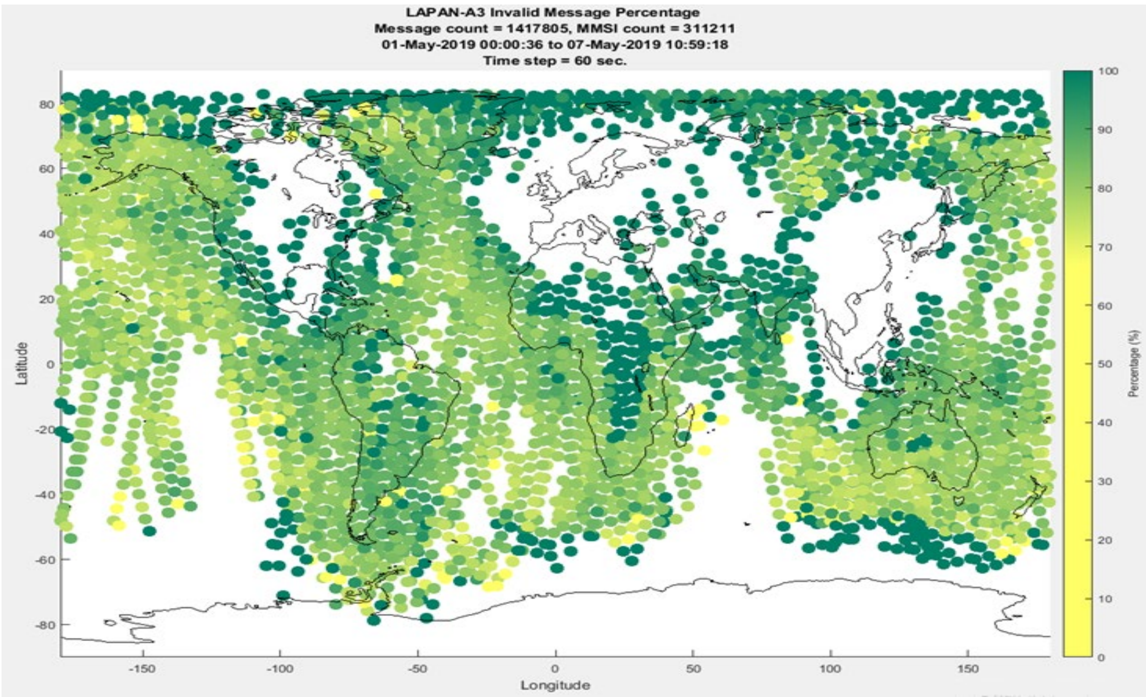

Figure 4.6 LAPAN-A3 invalid AIS message distribution from orbit.

Figure 4.6 shows that several areas with having a significant impact on the AIS messages quality. The map shows that several areas of the Gulf of Mexico, Mediterranean, English Channel, North Sea, Baltic Sea, Malaka strait, South, and the East China Sea significantly have bad CRC due to message collision. In those areas, it could be seen that the AIS message starts to get increasing in invalid CRC until it's saturated that there are even no AIS messages that could be received by satellite. Besides that, however, some interesting areas, such as the middle of the African continent, also have significant invalid AIS messages. This shows that the AIS message may interfere with the terrestrial VHF channel. The map also shows that the north and south pole has a significant invalid CRC AIS message.

Another way to find out the saturated area from AIS information could be done by developing a re-detection algorithm of the ship, since its assumption that if a ship could be detected for the first time, then it supposes could be detected afterward in the next satellite pass. The re-detection algorithm has been used for the AISsat-1 satellite [76]. This algorithm then applied to see the tracking capabilities and the LAPAN-A3 AIS data saturation area, as described below.

All space-based tracking capability and detection probability calculations have to be treated by pre-processing stages to remove incorrect messages.

- The very first step is removing duplicate messages from LAPAN-A3 AIS data collected from 10-14 October 2018. This step is essential since duplicate messages will lead to an incorrect final result caused by unnecessary repetitive calculations. After removing duplicate messages, AIS messages were filtered out to remove wrong MMSI identifiers reporting erroneous positions. This step was carried out by finding and removing MMSI identifiers reporting latitude value less than -90° or exceeding 90°. Similarly, MMSI identifiers reporting longitude values below -180° or greater than 180° were also removed.
- Next, to ensure dummy reporting location messages not included in subsequent processing, the SGP4 orbital mechanic's algorithm was employed to remove these dummy messages collected by space-based AIS. SGP4 was used to simulate satellite position and to determine its footprint on the earth at a particular time. All MMSI of space-based AIS collected on corresponding time reporting positions outside the satellite coverage will be excluded from subsequent processing. This correction is intended to ignore all MMSI identifiers transmitting dummy locations.
- The last, based on the fact that many MMSI identifiers are used by more than one ship, suspected re-used MMSI must be removed. To perform this step,

identifying and removing re-used MMSI identifiers by calculating the speed required to move between two points based on timestamps and positions recorded by the AIS system. If the calculated speed exceeds 60 knots, the MMSI is excluded. The remaining MMSI identifiers after passing through such pre-processing steps above are then included in the subsequent calculation.

Since the global area's tracking capability calculation is very extensive, the calculation must be carried out discretely. Therefore, the global area must be divided into grid cells so that the final result will represent the tracking capability and detection-probability of the particular area covered by those grid cells. In this work, a 2°×2° grid was used as the default parameter so that the Earth surface is divided into 90×180. A lower and higher grid size has not been investigated, but one must sensibly allow enough space for many ships to fit on the grid.

Estimating the tracking capability requires only the data recorded by the space-based AIS sensors themselves. For calculation purposes, the following definitions are used:

$N_{\mathrm{det}}^{\mathrm{MMSI}}(grid\ \ \mathrm{cell})_{T_{start}}^{T_{end}}$: The number of space-based AIS system accesses to the grid cell in which an MMSI was detected within a specified timeframe between T_{start} and T_{end}.

$N_{\mathrm{tot}}^{\mathrm{acces}}(grid\ \ \mathrm{cell})_{T_{start}}^{T_{end}}$: The total number of space-based AIS system accesses to the grid cell over the specified timeframe between T_{start} and T_{end}.

For detection purposes, a single message is sufficient per access to the area. Then, the space-based AIS system tracking capability of a particular MMSI in a particular grid cell, $TC_{\mathrm{MMSI}}(\text{grid cell})$, can be quantified by using Eq. (5. 20)

$$TC_{\mathrm{MMSI}}(\text{grid cell}) = \frac{N_{\mathrm{det}}^{\mathrm{MMSI}}(grid\ \mathrm{cell})_{T_{start}}^{T_{end}}}{N_{\mathrm{tot}}^{\mathrm{acces}}(grid\ \mathrm{cell})_{T_{start}}^{T_{end}}} \tag{4. 20}$$

If the tracking capability for a particular ship in a particular grid cell has been quantified according to Eq. (4.20), an average tracking capability for all MMSI per grid cell can be quantified according to Eq. (4. 21),

$$TC(\text{grid cell}) = \frac{\sum_{\mathrm{MMSI}} TC_{\mathrm{MMSI}}(\text{grid cell})}{N_{MMSI}(\text{grid cell})} \tag{4. 21}$$

where $N_{MMSI}(\text{grid cell})$ refers to the total unique MMSI identifiers seen by a space-based AIS system.

In general, to quantify the tracking capability as described by Eq. (4.20) and ultimately Eq. (4.21) following steps must be performed:

- Calculate the space-based AIS system's access time to every grid cell per orbit over the specified timeframe from orbital mechanics in order to enable calculation of $N_{\text{tot}}^{\text{access}}(grid\ \ \text{cell})_{T_{start}}^{T_{end}}$.
- Track the movements of each MMSI (ship) by using available position information reported by the ships over the analysis timeframe in order to calculate $N_{\text{det}}^{\text{MMSI}}(grid\ \ \text{cell})_{T_{start}}^{T_{end}}$
- Calculate the tracking capability per MMSI as per Eq. (4.1) and further quantify the average tracking capability for all MMSI per grid cell as per Eq. (4.2).

Once the average re-detection probability per grid cell has been calculated from Eq. (4.21), the results can be statistically accumulated to show the temporal evolution of the re-detection probability as the space-based AIS system observes a grid cell multiple times, according to Eq. (4.22),

$$P_{TC}^{acc}(\text{grid cell}) = \left(1 - \prod^{N_{\text{tot}}^{\text{access}}(grid\ \text{cell})}\left(1 - TC(\text{grid cell})\right)\right) \times 100\% \qquad (4.\ 22)$$

where $N_{\text{tot}}^{\text{access}}(grid\ \ \text{cell})$ refers to the number of space-based AIS system accesses to a grid cell within the accumulation time, calculated from the orbital mechanics' algorithm. The final result, $P_{TC}^{acc}(\text{grid cell})$ then assigned as a space-based AIS system performance index, i.e., tracking capability.

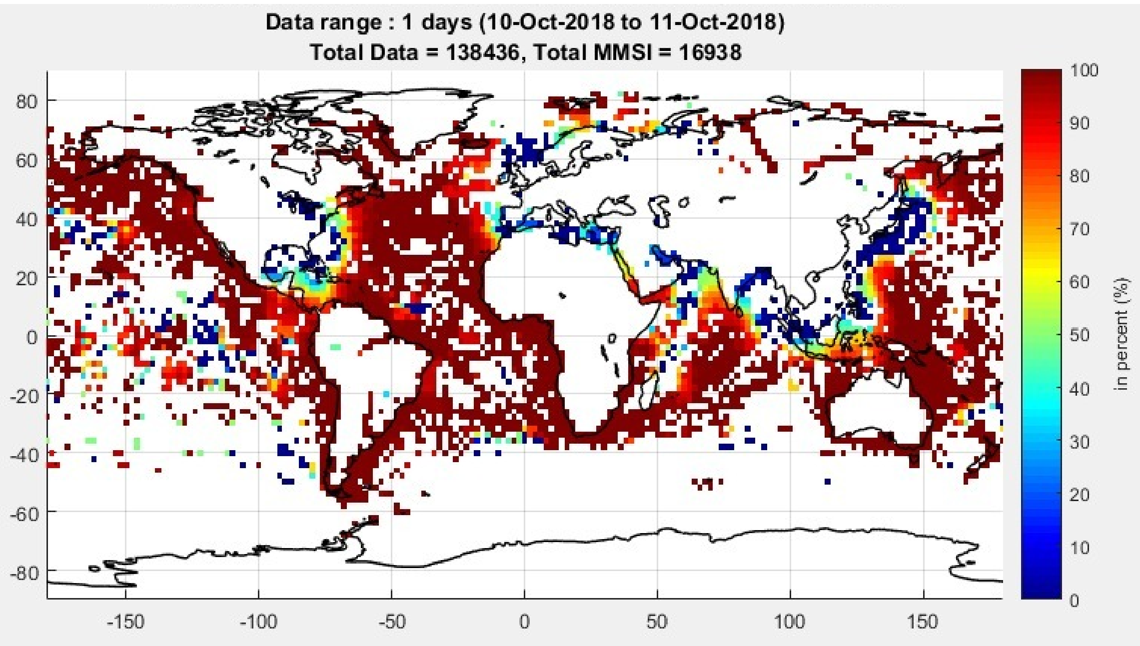

Figure 4.7 Probability re-detection of an already detected ship by LAPAN-A3. (24 hours)

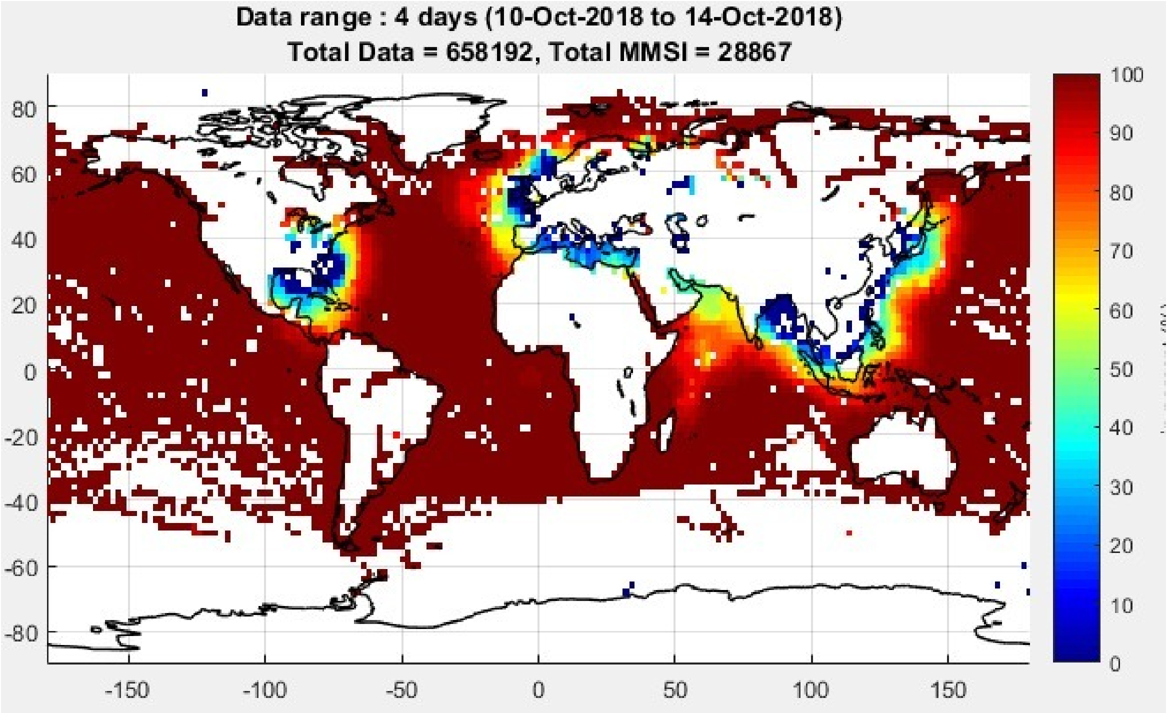

Figure 4.8 Probability re-detection of an already detected ship by LAPAN-A3. (4 days)

Figure 4.7 shows the probability re-detection of an already detected ship by LAPAN-A3 after 24 hours. From the map, there are still some areas without information on AIS messages. With the assumption that many ships still could not be detected in 24 hours, it is necessary to increase the detection duration to 4 days, as in Figure 4.8. From the map, it could be seen that in areas with a high ship density, and thus co-channel interference issues when viewed from space, such as the Gulf of Mexico, Mediterranean, English Channel, North Sea, Baltic Sea, Malaka Strait, South and the East China Sea, the re-detection probability is low. The result from the LAPAN-A3 satellite is in line with the result from AISSat-1 [76].

Besides the message collision that may happen in dense ships, there is also a characteristic of AIS transmission of each ship that affects the reception of AIS message in the satellite. Figure 4.9 shows several ships underway in Antarctica, which is supposed to be no message collision due to less traffic. One could see an ice breaker ship with MMSI 366610000 at first underway without any other ships around, and the message could be captured every 10 seconds, and only one message has bad CRC in the first 2 minutes by the satellite. Afterward, a crude oil tanker ship with MMSI 240168000 shows up and further some other cargo ships. However, with only six ships in the satellite footprint, the collision of AIS message probability should be less, and good satellite reception could be expected. Nevertheless, from the AIS data reception, it could be shown that each of the ships has a different characteristic of its AIS reception in the satellite footprint and also length of contact time to the satellite. The crude oil tanker has better access to the satellite; however, the ice breaker ships have some interrupt about half a minute after a certain message was delivered.

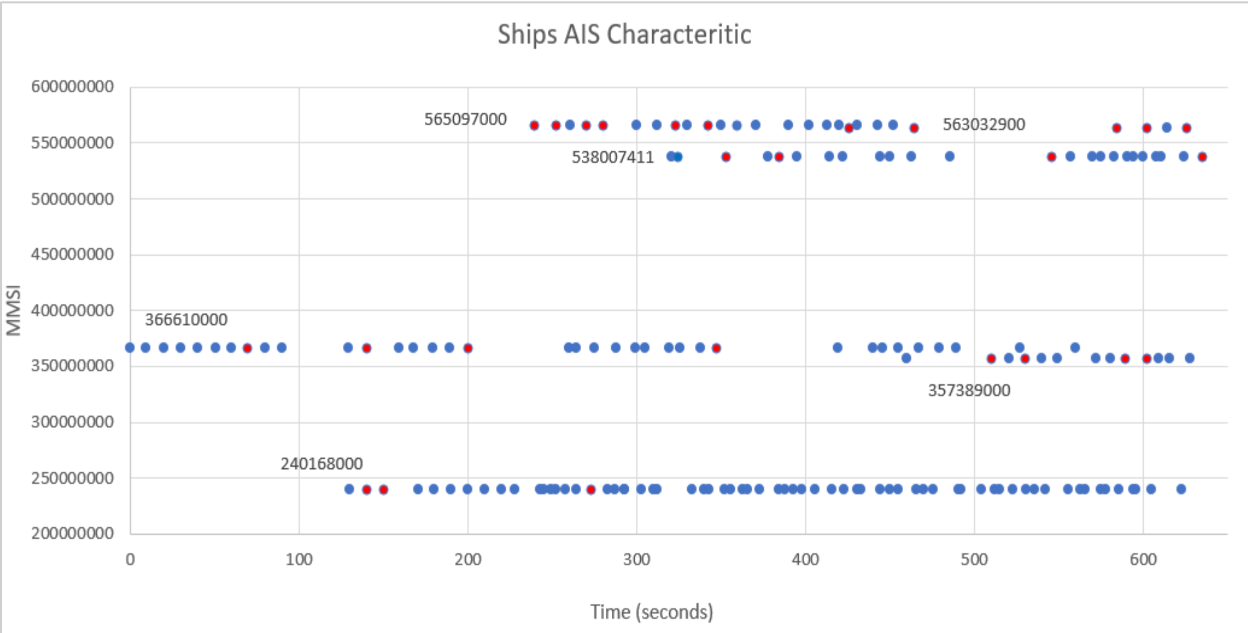

Figure 4.9 Ships underway in Antarctica.

5

Discussion of Potential Solutions of Satellite AIS Problem

5.1 New Frequencies and Longer Intervals

As mentioned in the previous section, it has been described that AIS information is transmitted in 2 VHF channel frequencies and additional two frequencies for long-range AIS messages. For the terrestrial receiver, these two frequencies are still appropriate due to the small reception area, and the probability for message collision is less compared if received by satellite. As in the previous section, the message collision probability is getting higher in the busy sea area. This collision challenges than need a technical and regulatory solution, since in some cases, a technical solution has some limitations. Hence, the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) proposing the VHF Data Exchange System (VDES).

VDES was generated by IALA to resolve emerging indications of AIS VHF Data Link (VDL) overload and simultaneously enable the maritime community to share more seamless data. The Automatic Identification System (AIS) roles, Applications Specific Messages (ASM), the VDE terrestrial portion, and the VDE satellite portion are included in the initial VDES definition. One of the possible elements of e-navigation is VDES. VDES is capable of ASM exchanging, facilitating various applications such as navigation safety and security, marine environment protection, and shipping effectiveness. VDES prospectively have a significant beneficial impact on the maritime information services, including Aids to Navigation (AtoN) and Vessel Traffic Service (VTS) in the future [77].

The VDES concept includes a satellite component. This system component might be suitable to be used for the transmission of MSI information in remote areas [78]. Insufficient study on sharing and compatibility between the VDE satellite component and incumbent services in the same and adjacent frequency bands was the cause that the spectrum issue could not be resolved at World Radiocommunication Conference in 2015 (WRC-15). As a consequence, VDES is still not a complete functional system as a whole. Consequential to WRC-15, the ITU standard for VDES, Recommendation ITU-R M.2092-0, was approved.

According to IALA Guideline 1117 "VDES Overview", the following potential VDES use cases are identified [79]:

- Search and rescue communications;
- Maritime Safety Information;
- Ship Reporting;
- Vessel Traffic Services;
- Charts and Publications;
- Route Exchange; and
- Logistics.

VDES satellite component would offer additional communications in polar regions and other remote areas for the above use cases. These use cases are all cross-referenced to Maritime Service Portfolios identified in IMO e-navigation Strategic Implementation Plan (SIM) and possibly also to the modernization of GMDSS in the future. The study of the candidate frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz would mainly concern the relationship with the existing services primarily allocated for the land mobile service and maritime mobile service, and with the services within the lower adjacent frequency band from 154 MHz to 156 MHz and for the higher adjacent frequency band from 162 MHz to 164 MHz.

Considering the above, the IMO's position in the issue is as follows [80]:

1. Recognizing that the VDES satellite component should not bring any harmful interference:
   - modifications should not be required to existing AIS equipment onboard existing vessels;
   - the integrity of the GMDSS should be protected;
   - identification of the frequencies for the VDES satellite component should protect the integrity of the original operational purpose of AIS on the existing AIS frequencies;
2. IMO supports the availability of VDES, including both terrestrial and satellite components.

In World Radiocommunication Conference (WRC) 2019 held in Sharm El-Sheikh, Egypt, in which the author was also involved as Indonesia member state delegation, a new secondary allocation frequency of 157.1875-157.3375 MHz dan 161.7875-161.9375 MHz for VDES has been approved. After several options and study by ITU, this new allocation has been defined and considering ITU member state's concern during that conference.

Besides new frequency allocation and creating a specific message for unloading the AIS channel, there is also a study to create a specific message of AIS transmission from the ship, especially for satellite detection, by increasing the longer this specific message transmission interval 3 minutes. The longer interval increase is beneficial since the probability of message collision in high-density ships area becomes lower from satellite reception. The recent improvements are made possible by adding the long-range message that is developed to support the reception of AIS messages by satellites to the AIS standard. Provided that more ships start using equipment supporting long-range AIS, the services may improve gradually with the current satellites through the long-range AIS capability and reducing message collision [81].

5.2 Smaller Beam Antenna & Other Technique

While the prospect of receiving AIS messages on a satellite is feasible and has already been demonstrated, AIS was initially designed for inter-vessel radio communications. Specifically, AIS signals are broadcast by the vessels to warn the surrounding vessels of their location, speed, and direction. This increases visibility and decreases the risk of collisions between vessels. The frequency of such messages depends on the vessel's speed, i.e., the higher the velocity, the more often the position update is broadcast through AIS messages.

In particular, the field of view of the satellite is an order of magnitude greater than the radio reception range of the vessel, e.g., around 1350 nm or 2500 km for a standard omnidirectional antenna (VHF) LEO satellite. It is, however, vulnerable to severe collisions between the packets of various ships. Channel sensing cannot be used by vessels well away from each other to allocate slots free from interference. In particular, this problem dramatically affects the detection efficiency of the AIS space-based system in densely-populated areas. Considering the increasingly growing traffic created by other maritime communication facilities assigned to the VHF band and the rise in vessels using AIS transceivers, this problem will be much more prevalent in the future.

A new AIS receiver optimization that can be used onboard the LEO satellite for space-based AIS systems is also recommended. The improved receiver intelligently uses side information that can be retrieved from satellite location information and a priori known fields in the AIS packet payload. This knowledge is then used to enhance the assessment of the channel, which inevitably increases the performance. AIS messages processed in the previous frames are often used to enhance vessel tracking in the satellite's first pass [82].

The ability to segment the field of view of a satellite into smaller views can be obtained by using Spot Beam Technology. Spot Beam Technology will segment the field of view of the satellite into a variety of smaller fields of view. The number of vessels in each narrower field of view is also limited for each of the beams. As a result, the number of messages originating from the various ship vessels in any of the smaller fields of view is significantly lowered. Therefore, using spot beam technology, the vessel's detection probability from a satellite can be significantly increased. For the optimized satellite, the ship detection probability for the AIS packet class with the lowest transmission frequency is seen to be very high. A standard LEO satellite, the DLR's AISat-1, has shown significant advantages from the two reduced footprints, especially in densely vessel-populated regions [83].

5.2.1 LAPAN-A2 AIS Antenna Orientation Study

The study has been carried out by maneuvering the attitude of LAPAN-A2, with an AIS antenna fixedly mounted on the satellite’s body, into the desired orientation [84]. The satellite AIS is typically small; a nano-sized or micro-sized satellite is suggested. The size limitation of the satellite AIS may cause various problems that need to be addressed, and one of the main problems is the antenna placement. The small size of the satellite limits the space and number of onboard antennas, causing communication problems. Smaller antennas lead to smaller power-to-noise ratios, and therefore reduced signal reception. For a nano-sized satellite, the reflector antennas are likely to require too much mass and volume. They are, therefore, mostly ruled out as an option even though there is a nanosatellite using a deployable Yagi-Uda type antenna [42]. Still, there exists a variety of thin linear antennas suitable for this type of satellite. A short linear conductor is often referred to as a short dipole. The conductor's length must be in the order of magnitude of the carrier's wavelength for the antenna to function properly, and different conductor lengths result in different field patterns. Even though LAPAN-A2 is not a nanosatellite, it is a small satellite carrying multiple payloads; hence there is a space limitation to place the directional antenna or dual polarization antenna. The AIS antenna orientation maneuvered in three orientations, as shown in Figure 5.1.

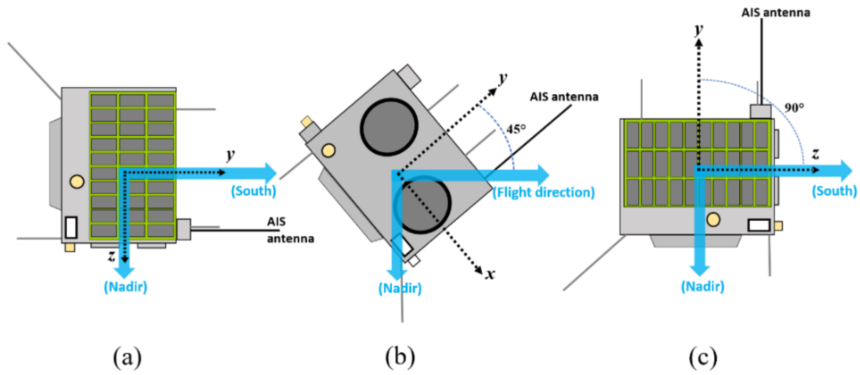

Figure 5.1 Illustration of LAPAN-A2 maneuvering configuration. (**a**) nadir, (**b**) 45°-maneuvered, (**c**) 90°-maneuvered [84].

Figure 5.2 provides the typical pattern of monopole antenna in a different orientation toward the ground. It is shown that the antenna pattern of LAPAN-A2 during 90°-maneuver or the vertical antenna position has a broader area of detection compared to the nadir and 45°-maneuver configurations. The broader detection could lead to the increase of message reception; however, at the same time, it may have a collision problem of the AIS signal. The AIS messages have been recorded and analyzed using the nadir, 45°-maneuvered, and 90°-maneuvered flight configurations.

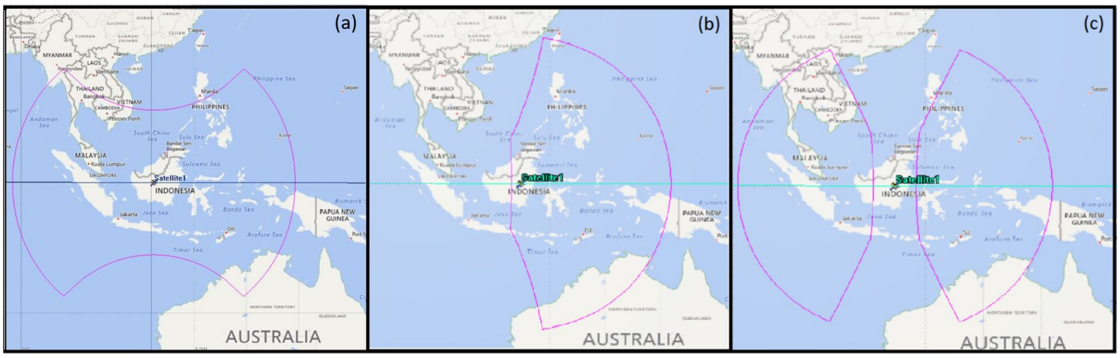

Figure 5.2 Typical antenna pattern of LAPAN-A2 AIS Antenna (**a**) nadir satellite attitude mode; (**b**) 45°-maneuvered; (**c**) 90°-maneuvered [84].

Figure 5.2 shows that the orientation of the monopole AIS antenna of LAPAN-A2 to 45 degrees will have a smaller field of view compared with the other two orientations.

The analysis of the impact of varying the orientation of monopole λ/4 AIS antenna on its message reception performance has been carried out within this study. The analysis shows by involving AIS datasets collected under 45°-maneuvered and 90°-maneuvered flight configuration applied on LAPAN-A2. In this case, the 45°-maneuvered and 90°-maneuvered, respectively, refer to the satellite attitude configuration in which the antenna is oriented 45 and 90° towards the satellite flight direction. Based on the analysis of those datasets, it is confirmed that the highest message reception performance can be achieved by orienting the monopole λ/4 antenna 45° toward the flight direction. This antenna orientation gives a significant increase in overall AIS messages reception, including class A and class B type ships. This finding recommends a small satellite or other satellite type carrying AIS payload to mount its monopole antenna orientation 45° towards its orbital flight direction.

5.3 Estimating Value of Ship Information from Invalid CRC Data of LAPAN Satellite AIS Data

The previous section explains that AIS data from LAPAN Satellite use CRC information to validate the AIS information chain received from the ships until the data has been downloaded in the ground station. Table 3.2 shows four CRC types, and from those CRC, only CRC of 10 is the valid CRC.

The invalid CRC AIS data, however, could still be used in some cases. The possibility of estimating the correct value from invalid CRC of AIS data could still be performed since the time of all AIS data received from the ships is stamping externally with satellite time. While assuming that the time is valid and at least two valid CRC of AIS data in some limited range of time, some value in the invalid CRC data could be estimated. A minimum of two valid data is needed so that it could be used to interpolate and also extrapolate the estimated position, speed, and course of the invalid CRC of AIS data. However, the invalid CRC of AIS data should have the same MMSI number as those valid CRC AIS data. Other than these criteria, then this method is not to be applied.

Figure 5.3 shows the algorithm to estimate the correct position, speed, and course of AIS data as its CRC is invalid.

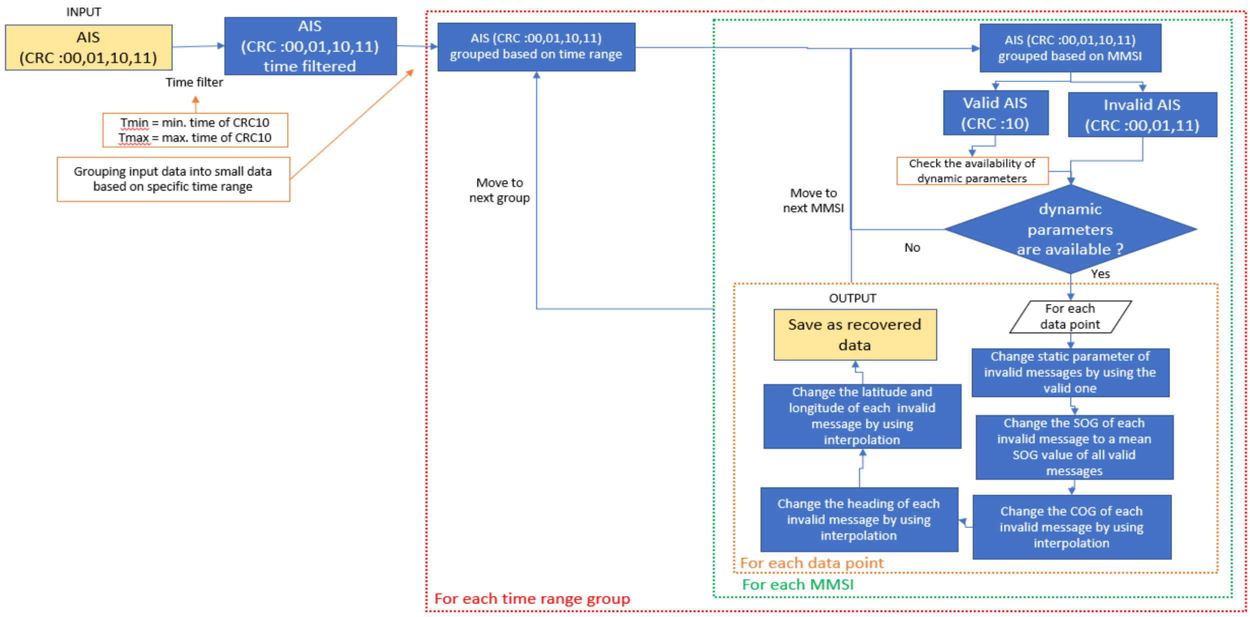

Figure 5.3 Algorithm to correct the position of invalid CRC AIS messages.

The reason to choose 10-12 minutes for this method is the satellite visibility above an area and avoiding less accurate extrapolation or interpolation of the data if the time range is too long. The steps for estimating the value of invalid CRC are given below:

- The input data used in the experiment is a dataset consisted of valid and invalid AIS messages that can be identified by their CRC sign. For simplicity, the input data is labeled as D. The CRC equals to '10' refers to valid messages while the other sign indicating invalid messages. The invalid and valid message datasets, respectively, are labeled as D_{val} and D_{inv}.

$$D = \{D_{val}, D_{inv}\} \quad (5.1)$$

- Since the correction algorithm is not intended to correct the invalid 'timestamp' of a particular invalid message, for the first time, we have included only all messages, D (valid and invalid) that having timestamp (t), $T_{min} \leq t \leq T_{max}$. The T_{min} and T_{max}, respectively, are the minimum and maximum timestamps of all given valid messages (D_{val}). The dataset D, after excluding out of timestamp data, can be re-write as follow:

$$D = D(T_{min} \leq t \leq T_{max}) \quad (5.2)$$

- After time filtering, the data is then sorted ascendingly based on their timestamp and grouped into a smaller dataset based on a specific time range (t_r). The t_r value is set to 12 minutes. The small group of the time-range-separated dataset is then noted as D_{tr}.

$$D^g = D(t_{start}(g) \leq t \leq t_{end}(g)) \quad (5.3)$$

The D^g refers to g-th group of small D with g = 0, 1, 2, … n-1. The n is the total group that can be calculated by using the following equation:

$$n = ceil\left(\frac{T_{max} - T_{min}}{t_r}\right) \tag{5.4}$$

The $t_{start}(g)$ and $t_{end}(g)$ are the start and end time of g-th group that can be defined by the following equation :

$$t_{start}(g) = T_{min} + g.t_r \tag{5.5}$$

$$t_{end}(g) = T_{min} + ((g + 1).t_r) \tag{5.6}$$

- For each group of time range data (D^g), the messages are then classified by their MMSI identifier, D^g_{MMSI}. Then, for each MMSI identifier, the data is then separated into two groups; valid ($D^g_{MMSI,val}$) and invalid ($D^g_{MMSI,inv}$) messages that can be identified by their CRC sign. For the sake of simplicity, the i-th data point of the invalid message and j-th datapoint of valid messages of a given MMSI on g-th group will be re-assign as d^i_{val} and d^j_{inv}. For convenience, the summary of dataset nomenclature is provided in Figure 5.4 below :

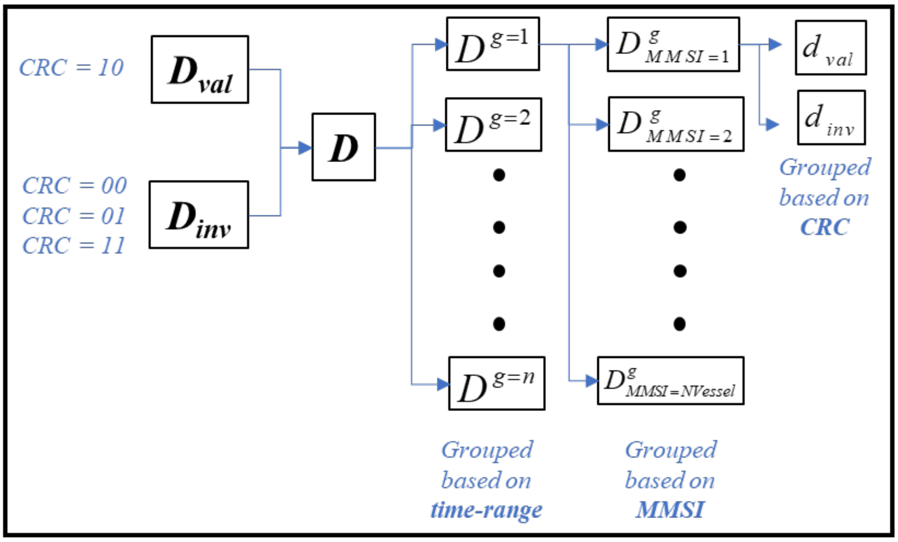

Figure 5.4 Summary of dataset nomenclature.

- The performance of the correction algorithm to recover invalid messages depends on the availability of valid messages d_{val} as the corrector dataset. Therefore, the availability of valid messages having dynamic parameter value (SOG, COG, latitude (λ), longitude (φ), and heading (θ) is compulsory as an initial requirement.
- Since a valid message may also contain invalid dynamic parameter values, a checking process has also been applied to these messages. The invalid dynamic parameter term refers to an "n/a" or blank values that indicate no available data for AIS messages'

particular dynamic parameter. This type of value cannot be used in the correction process and must be excluded from the corrector dataset.

- If there are exits, at least two invalid messages having all valid dynamic parameters of a given MMSId_{val} ($N_{val} > 2$), the process is continued to the next process, i.e., invalid message recovery. The invalid message recovery is performed by following the step as given below:

  - Change the static parameter of invalid messages by using the parameters of the valid message. These static parameters, including "message ID (MID) " and "Rate of Turn Indicator (ROT)".

$$d_{inv}^{i}(MID) = d_{val}^{1}(MID) \tag{5. 7}$$

$$d_{inv}^{i}(ROT) = d_{val}^{1}(ROT) \tag{5. 8}$$

    The $d_{val}^{1}(MID)$ and $d_{val}^{1}(ROT)$ refer to the first data point of valid messages dataset having valid message ID and rate of turn.

  - Change the SOG and COG of each invalid message by a mean value of SOG and COG of valid messages, respectively.

$$d_{inv}^{i}(SOG) = \frac{\sum_{j=1}^{N} d_{val}^{j}(SOG)}{N} \tag{5. 9}$$

$$d_{inv}^{i}(COG) = \frac{\sum_{j=1}^{N} d_{val}^{j}(COG)}{N} \tag{5. 10}$$

    The *N* denotes a total number of the valid messages having valid SOG value. Since SOG and COG of a valid message can be null or invalid, a limitation applied that the only ship having SOG and COG 0 – 60 knots will be included in the mean calculation. Therefore, the d_{val}on equation (5. 9) is resulted by performing the filtering process given below

$$d_{val}(SOG) = d_{val}(0 \leq SOG \leq V_{max}) \tag{5. 11}$$

$$d_{val}(COG) = d_{val}(0 \leq COG \leq V_{max}) \tag{5. 12}$$

    which $V_{max}$is set to 60 knots.

  - The heading (θ), latitude (λ), longitude (γ), of each invalid message is replaced by the estimated values that can be achieved based on three different conditions.

    Condition 1: The invalid datapoint is detected before any valid data points were found, as illustrated in Figure 5.5 below.

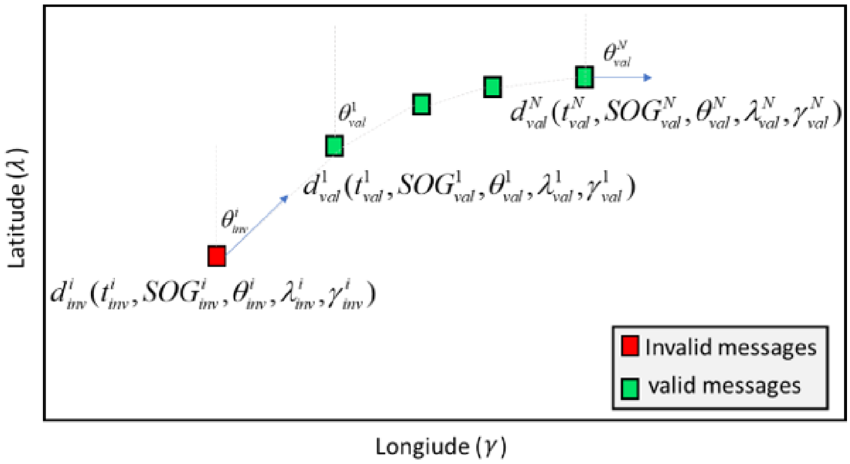

Figure 5.5 Illustration of condition 1.

In this condition, the d_{val}^{1}will be used to estimated dynamic parameters of d_{inv}^{i}. To estimate new $\lambda_{inv}^{i}, \gamma_{inv}^{i}$ value, distance traveled (r) from $(\lambda_{val}^{1}, \gamma_{val}^{1})$ to those new estimated points must be calculated:

$$r = SOG_{val}^{1}.(t_{val}^{1} - t_{inv}^{i}) \tag{5. 13}$$

The value of $(\lambda_{inv}^{i}, \gamma_{inv}^{i})$ can be estimated by using the Haversine method, as illustrated in Figure 5.6. This method is used to estimate latitude and longitude value from given initial latitude, longitude, bearing β, and distance r.

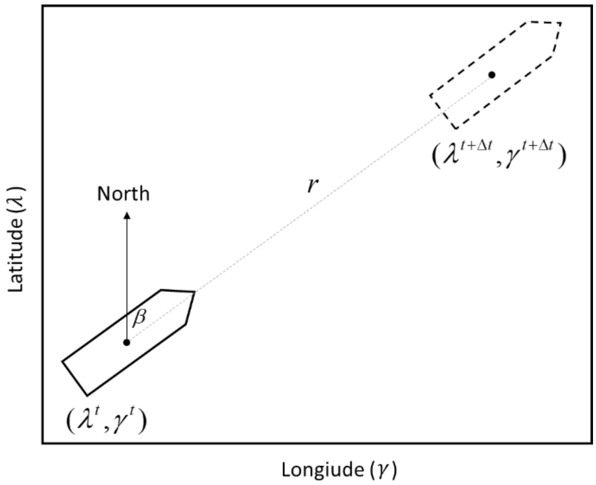

Figure 5.6 Illustration of the Haversine formula.

Therefore, by using $\lambda_{val}^{1}, \gamma_{val}^{1}$as the origin point $(\lambda^{t}, \gamma^{t})$, $(\theta_{val}^{1} - 180)$ as the bearing β and distance r, the $(\lambda_{inv}^{i}, \gamma_{inv}^{i})$ in radian is calculated as follow :

$$\lambda_{inv}^{i} = sin^{-1}\left(sin\lambda^{t}.cos\left(\frac{r}{R}\right) + cos\lambda^{t}.sin\left(\frac{r}{R}\right).cos\,\beta\right) \tag{5. 14}$$

$$\gamma_{inv}^{i} = \gamma^{t} + tan^{-1}\left(\frac{sin\,\beta.sin\left(\frac{r}{R}\right).cos\gamma^{t}}{cos\left(\frac{r}{R}\right) - sin\lambda^{t}.sin\lambda_{inv}^{i}}\right) \tag{5. 15}$$

The λ^i_{inv}used in equation (5.15) is estimated valued resulted from (5.14) while R is radius constant (6378.1 km).

Condition 2: The invalid data point is detected after all valid data points were found as illustrated in Figure 5.7 below.

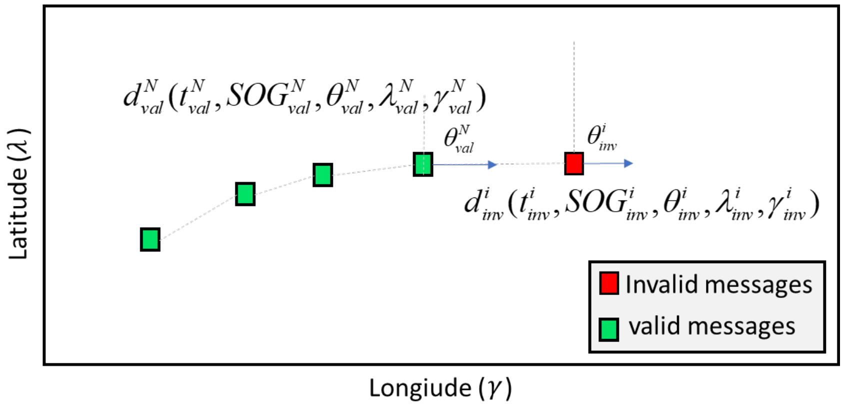

Figure 5.7 Illustration of condition 2

For this condition, the $d^N_{val}$is used as a corrector point. Therefore, the Haversine calculation as given in (5.14) and (5.15) can be used to estimate the $(\lambda^i_{inv}, \gamma^i_{inv})$ by assigning $\lambda^N_{val}, \gamma^N_{val}$as the origin point ($\lambda^t$,γ^t), θ^N_{val}as the bearing β, and distance r. However, the r-value must be re-calculated by following the equation below:

$$r = SOG^N_{val}.(t^i_{inv} - t^1_{val}) \tag{5. 16}$$

Condition 3: The invalid data point is found between the valid points, as in Figure 5.8.

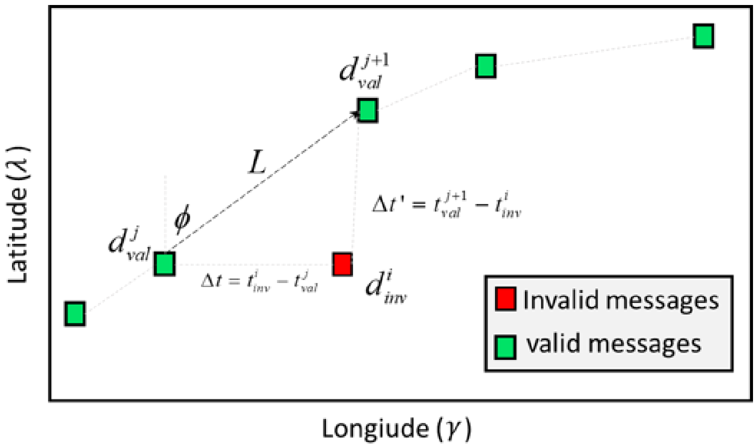

Figure 5.8 Illustration of condition 3.

For this case, the corrected $\lambda_{inv}^{i}, \gamma_{inv}^{i}$ is always located along the connecting line L. Therefore, the bearing angle is not as a function of θ_{val}^{j}or θ_{val}^{j+1}, because it can be estimated using two valid positions of d_{val}^{j}dan d_{val}^{j+1} by using equation (5.17) below:

$$\phi = tan^{-1}\left(\frac{cos\lambda_{val}^{j+1}.sin\left(\gamma_{val}^{j+1}-\gamma_{val}^{j}\right)}{cos\lambda_{val}^{j}.sin\lambda_{val}^{j+1} - sin\lambda_{val}^{j}.cos\lambda_{val}^{j+1}.cos\left(\gamma_{val}^{j+1}-\gamma_{val}^{j}\right)}\right) \quad (5.17)$$

There are two possible conditions to decide the corrector data point. If $\Delta t \leq \Delta t'$, the d_{val}^{j} used as the corrector data point. In this condition, the corrected $\lambda_{inv}^{i}, \gamma_{inv}^{i}$are estimated using the Haversine formula as given in (5.14) and (5.15) by assigning $\lambda_{val}^{j}, \gamma_{val}^{j}$as the origin point ($\lambda^{t}$,γ^{t}), ϕas the bearing β, and distance *r*. The *r* can be calculated using:

$$r = SOG_{val}^{j}.\Delta t \quad (5.18)$$

However, if $\Delta t > \Delta t'$, then the d_{val}^{j+1}will be used as the corrector data point. Then, the corrected $\lambda_{inv}^{i}, \gamma_{inv}^{i}$are estimated using the equation (5.14) and (5.15) by assigning $\lambda_{val}^{j+1}, \gamma_{val}^{j=1}$as the origin point ($\lambda^{t}$,γ^{t}), $(\phi - 180)$ as the bearing β, and distance *r*. The *r* is re-calculated using:

$$r = SOG_{val}^{j+1}.\Delta t' \quad (5.19)$$

- In the end, the CRC of recovered messages with estimation value is then assigned to ‘22’.

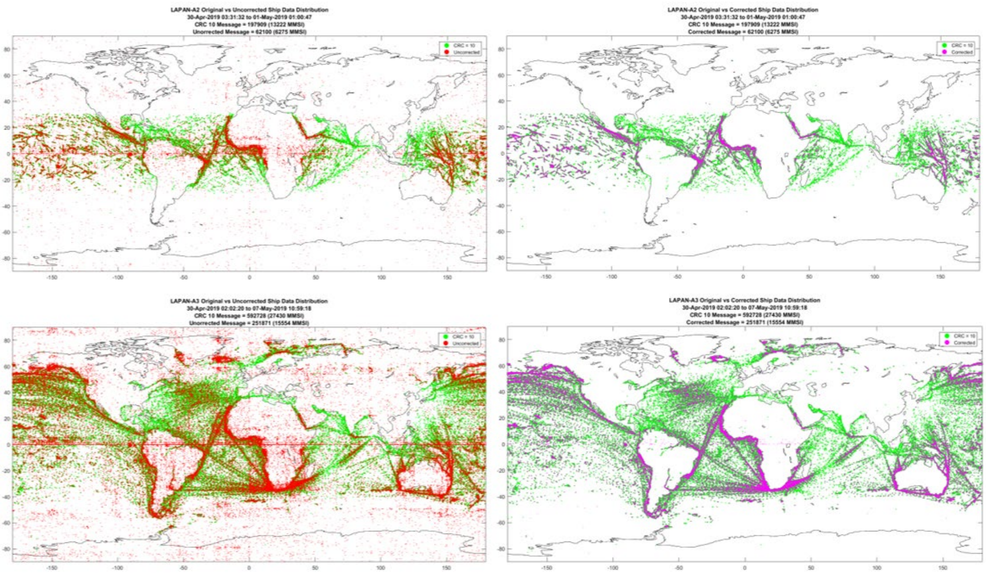

Figure 5.9 Left Image: a combination of invalid and valid CRC of LAPAN-A2 and LAPAN-A3 satellite AIS data (invalid: red; valid: green). Right image: a combination of valid CRC and estimation value from invalid CRC of AIS data (valid: green; estimation: magenta)

Figure 5.9 shows that many invalid CRC of AIS data affecting the position information of the ships. In LAPAN-A2 AIS data, there is much wrong information about the ship's position due to the bit error during the data communication as much information coming from ships beyond ± 25 degrees latitude and from the land. For LAPAN-A3, much wrong information is shown coming from surround land.

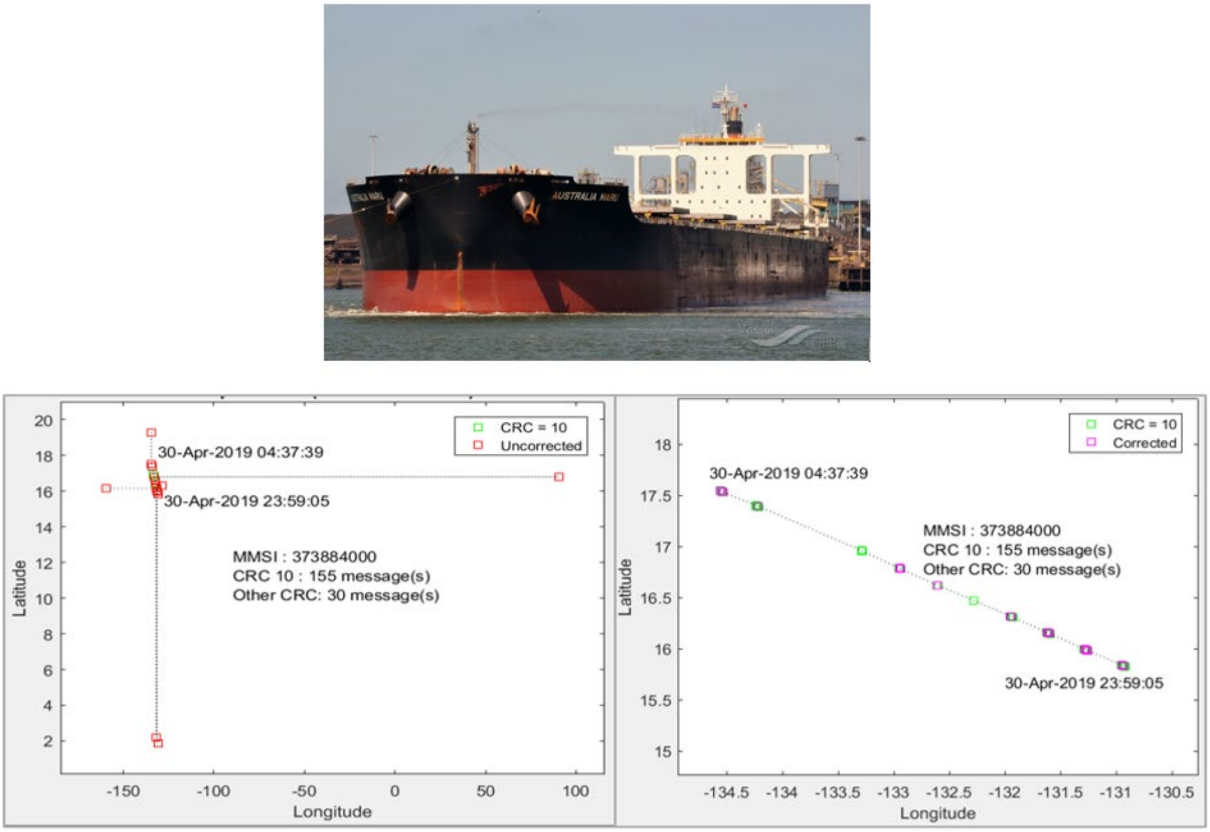

Figure 5.10, a Bulk carrier (top) with valid CRC and invalid CRC of AIS data (left) and after estimating the value from invalid CRC of AIS data. (*ship photo by marcel coster via www.vesselfinder.com*)

Figure 5.10 shows an example of a ship with MMSI 373884000 with its valid and invalid CRC of AIS data. Before implementing the estimation method, one could see that the 30 messages are invalid and show much wrong information since its position jump drastically from different latitude and longitude within a few hours. After applying the estimation method using its valid CRC of AIS data, the ship's complete information makes more sense as it is underway in a particular direction.

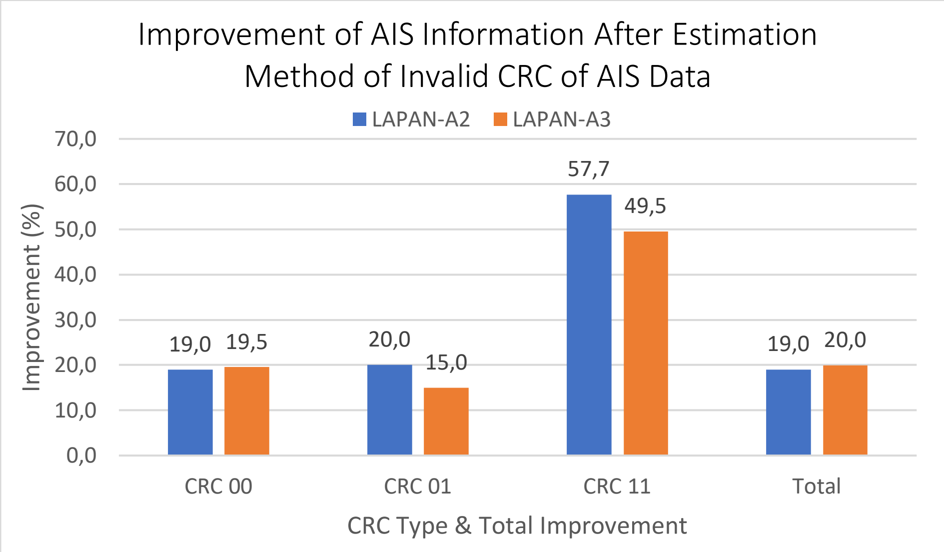

Figure 5.11 Improvement of AIS information after estimation method applied.

After applying the estimation method for the invalid CRC data, some improvements are shown from several CRC in Figure 5.11, especially for CRC 11, which improves between 49 to 57% from its original data. CRC 11 means that the ship's information is correct; however, some errors happen in the transmission when the data is sent to the ground. However, the CRC 00 and 01 are difficult to be estimated since the bit error already happens when the ship transmits its AIS data, and a collision happens when the date received by satellite or the bit error already affected the MMSI of the AIS data. By using this approach, invalid CRC of AIS data could still be used.

6

Optical Observation with Satellites

6.1 Experience with Optical Ship Observation

Based on the benefit of a relatively lower cost but still has an optimum mission application, LAPAN established cooperation with Technische Universität Berlin in 2003 to developed LAPAN-TUBSAT Satellite.

LAPAN-TUBSAT is the first research satellite of Indonesia based on the existing TUBSAT satellite heritage. The spacecraft structure is an Al alloy box of 45 cm x 45 cm x 27 cm and a mass of 56 kg. The various subsystems are mounted onto two shelves and carry two video cameras with low resolution and high resolution. The satellite mission is intended for technology demonstration and earth surveillance [46]. The satellite was launched on 10 January 2007 with PSLV-C4 from India. During the satellite operation with interactive attitude control, many interesting areas were captured by the satellite and its video processed for surveillance, including remote sensing applications [85]. The satellite still in operation when writing even though it lost one cell of its battery in 2015 and lost the high-resolution camera image after five years in orbit. Other than that, the subsystem is still in good condition even after 13 years in orbit.

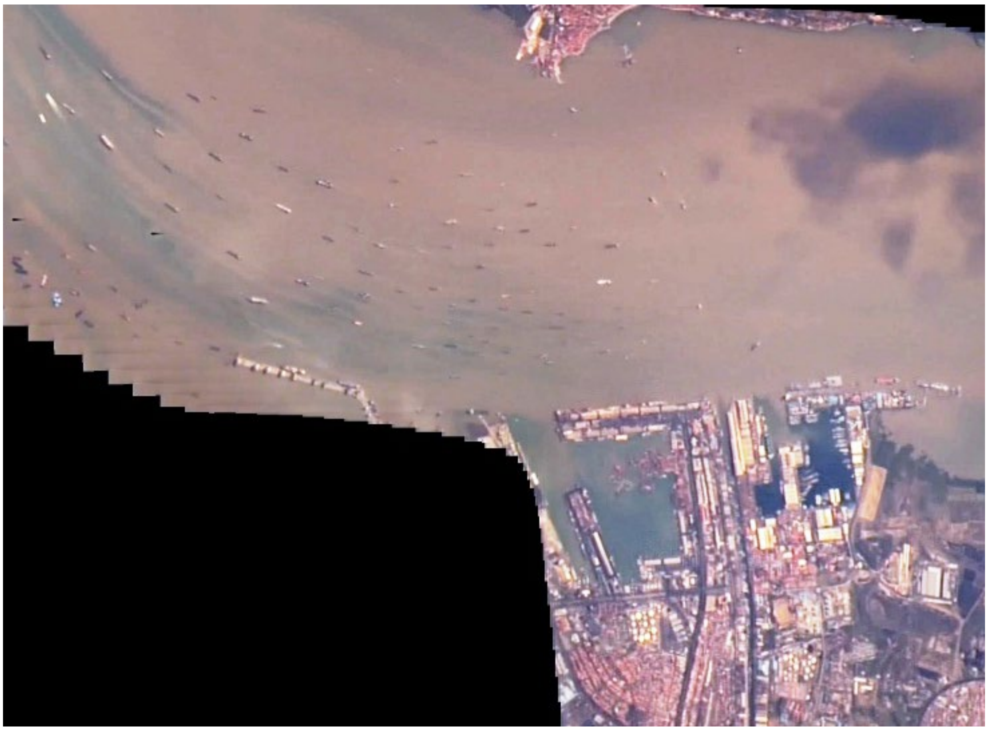

Figure 6.1 Stitched image of LAPAN-TUBSAT satellite over Surabaya Harbor, Indonesia.

Figure 6.2 Stitched image of LAPAN-TUBSAT Satellite in Napoli, Italy.

Figure 6.1 and Figure 6.2 shows an image of ships of various sizes. With the resolution of 5 meters, the big ships longer than 50 meters could be easily identified. In 2007 when LAPAN-TUBSAT has launched, the AIS regulation just three years in implementation. While looking for the image resulted from LAPAN-TUBSAT and the potential of the optical camera of the satellite to monitor the ocean, there was a discussion to include AIS in the next LAPAN Satellite. During that satellite design phase, the combination of High Definition Video Camera (HDTV) combined with AIS as a satellite payload also becomes an idea. This idea was then realized with LAPAN-A2 and LAPAN-A3 Satellites. However, HDTV payload could not be realized and replaced with other optical cameras during the time development of the LAPAN-A2 Satellite. The data rate and high complexity of HDTV processing were challenging to be implemented in the small satellite class at that time.

6.2 Overlay of Optical Images with Satellite AIS Data

From the perspectives of data sources, ship recognition can be generally divided into three domains: synthetic aperture radar (SAR) images, infrared (IR) images, and visible remote sensing (VRS) images. Because the synthetic aperture radar (SAR) method can image day and night regardless of weather conditions, all SAR-based methods expend significantly, achieving impressive performance. However, identification failures can arise from the invisibility of small and wooden boats in SAR images. In addition, the lack of color and texture characteristics, as in Figure 6.3, makes SAR scenery unfavorable for the ship targets to be identified [86]. IR images are employed to enhance the visual effect in weak light conditions. However, they also have some drawbacks, such as low signal-to-noise ratio, insufficient structure information, and varied gray levels [87]. Compared with SAR and IR images, the visible images investigated in this thesis are more intuitive and capture more details and complex structures of an observed scene. The satellite's visible image can be further used in the target recognition, such as in Figure 6.4, which shows the typical potential transshipment of 2 ships in the sea (inset). However, the facts mentioned above about visible images complicate the background and pose three main challenges to ship detection [88] [3]:

- The high variability of targets is generated, such as by a change in point of view, image sensor parameters, occlusion, ship wakes, ship color, speed, and ship material.
- High false alarm rate due to islands, heavy clouds, ocean waves, and the various and uncertain sea state conditions, like partial cloud cover, fog, wind, and swell.

- The third problem is the burden of computation. There is a high computational impact on most detection techniques. Therefore, for large-scale remote sensing images, reducing computational costs is considered a critical problem.

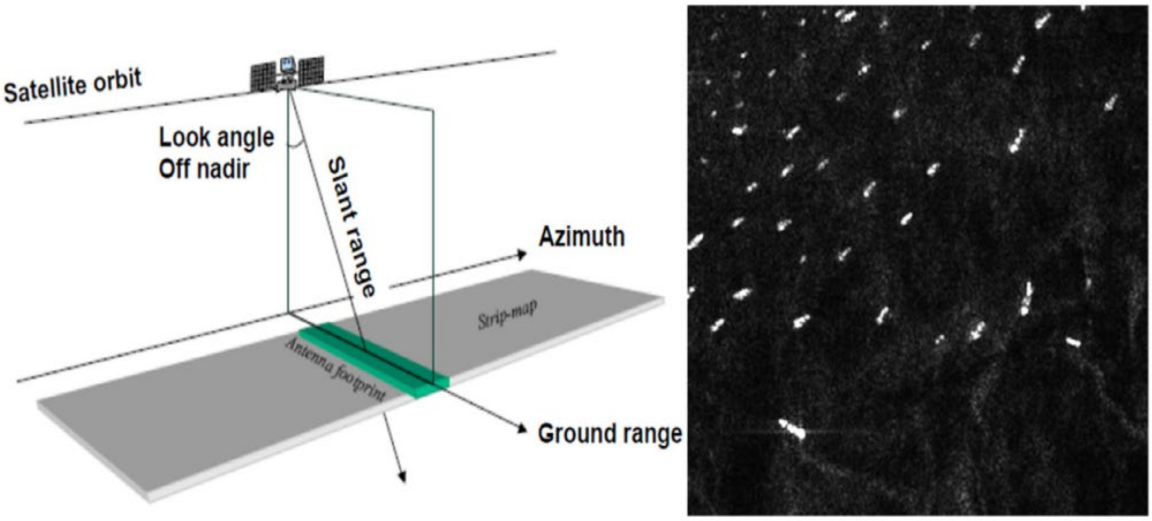

Figure 6.3 Typical of ship image-derived from SAR satellite [89]

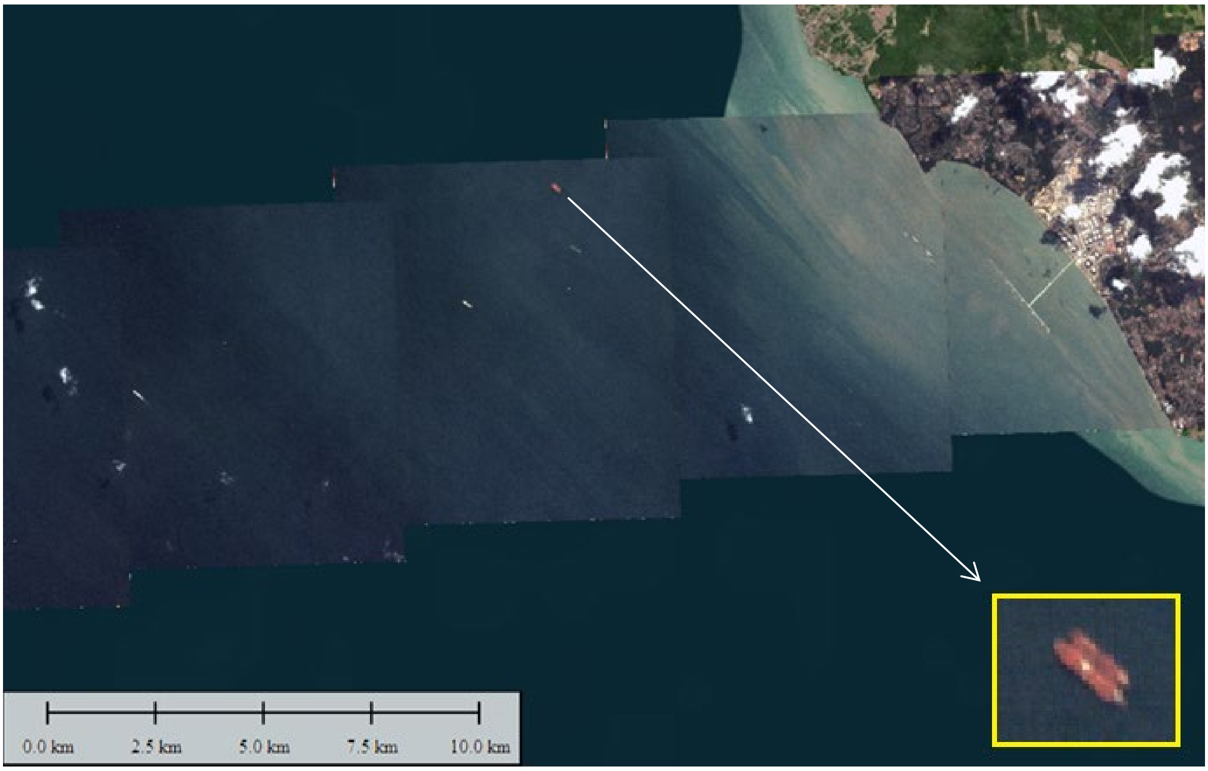

Figure 6.4 LAPAN-A2 satellite capturing ship images in Malaka Strait on 6 May 2019 at 02:55:15 UTC.

As discussed in the previous chapter, the fusion of AIS and satellite image is crucial since it compares cooperative and non-cooperative surveillance systems to get detailed information on a ship. However, the time gap of data fusion is essential. For the case monitoring anchor or moored of ships, the time gap is not significantly important. However, the time gap between image and AIS information becomes crucial for monitoring the moving ship, especially in dense vessel area. The relation between the time gap in AIS information and satellite image results in data fusion accuracy. For a given delay time, *Td*, the error in a distance of ship moving with constant velocity *v* can be calculated as follow:

$$\Delta R = v.T_d \tag{6.1}$$

Based on the equation above, the higher the delay time, the larger the distance error is. However, the maximum value of ΔR is limited by the maximum satellite visibility duration (T_{sat}) and the ship's maximum speed in general (V_{max}) based on Table 2.2. The maximum value of distance error ΔR_{max} can be calculated by multiplying the T_{sat} with maximum ship velocity V_{max} = 23 knots (709.93 m/mins).

$$\Delta R_{max} = T_{sat}.V_{max} \tag{6.2}$$

The T_{sat} itself is dependent on particular satellite altitude H in which can be calculated as given below.

$$T_{sat}(H) = P(H).\left(\frac{90 - sin^{-1}\left(\frac{R_E}{R_E+H}\right)}{180}\right) \tag{6.3}$$

The R_E is Earth radius constant set to 6,378.14 km, and $P(H)$ is a satellite orbital period that also depends on the H in which can be calculated using:

$$P(H) = 1.658669 \times 10^{-4} \times (6{,}378.14 + H)^{3/2} \tag{6.4}$$

For an LEO satellite having an altitude 650 km above the earth, the T_{sat} is equal to 13.49 minutes; hence, the ΔR_{max} equals to 10.29 km.

This ΔR_{max} value is used to convert the distance error into a general metric expressing detection accuracy A_{CC} as given below:

$$A_{CC} = \left(1 - \left(\frac{\Delta R}{\Delta R_{max}}\right)\right) \times 100\% \quad (6.5)$$

The simulation results of this problem using T_{sat} 13.49 minutes are given in Figure 6.5 below:

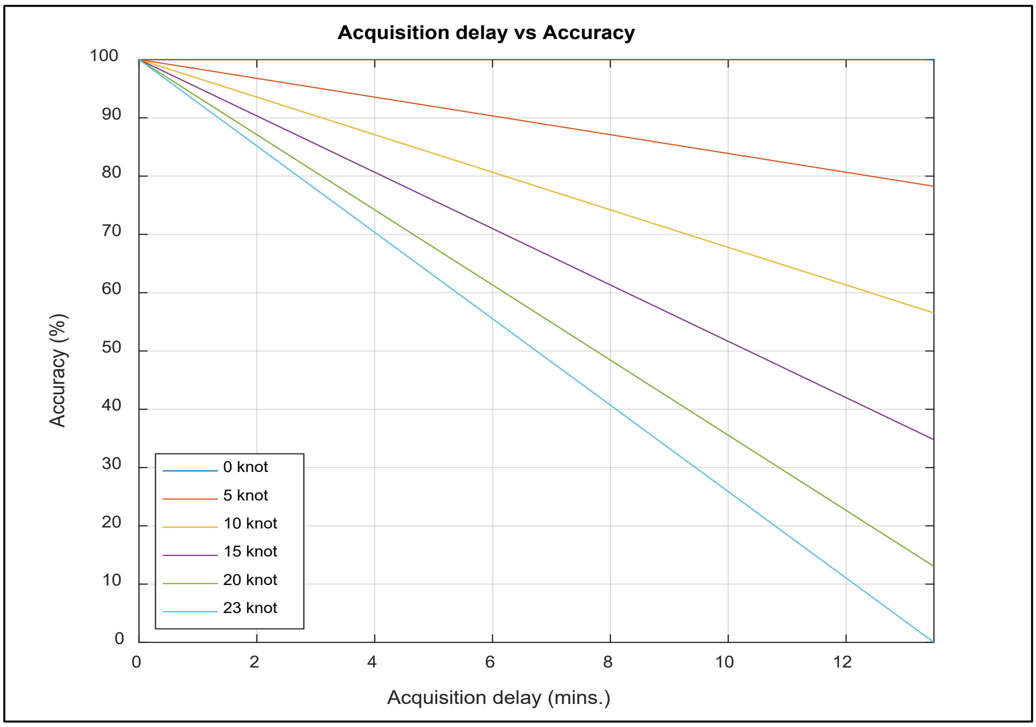

Figure 6.5 Accuracy of AIS and satellite image combination versus its time gap.

As explained in the previous chapter, LAPAN-A2 and LAPAN-A3 satellites could also capture the image while capturing the ship's AIS data. This combination payload of AIS and imaging in one satellite platform is the first time implemented in a satellite system. For this thesis, several ship images samples have been captured and included recording its AIS simultaneously from each of the satellites. The images discussed in this section are taken between 2018 and 2019 and with minimum cloud cover since identification from the optical camera could not be made if it is full of cloud.

The figure below shows the flow of image processing from the LAPAN satellite. As mention in the previous section, LAPAN-A2 has a high-resolution digital camera, and LAPAN-A3 has a multispectral camera with medium resolution. There is the procedure to process the image data, as mentioned in Figure 6.6 below.

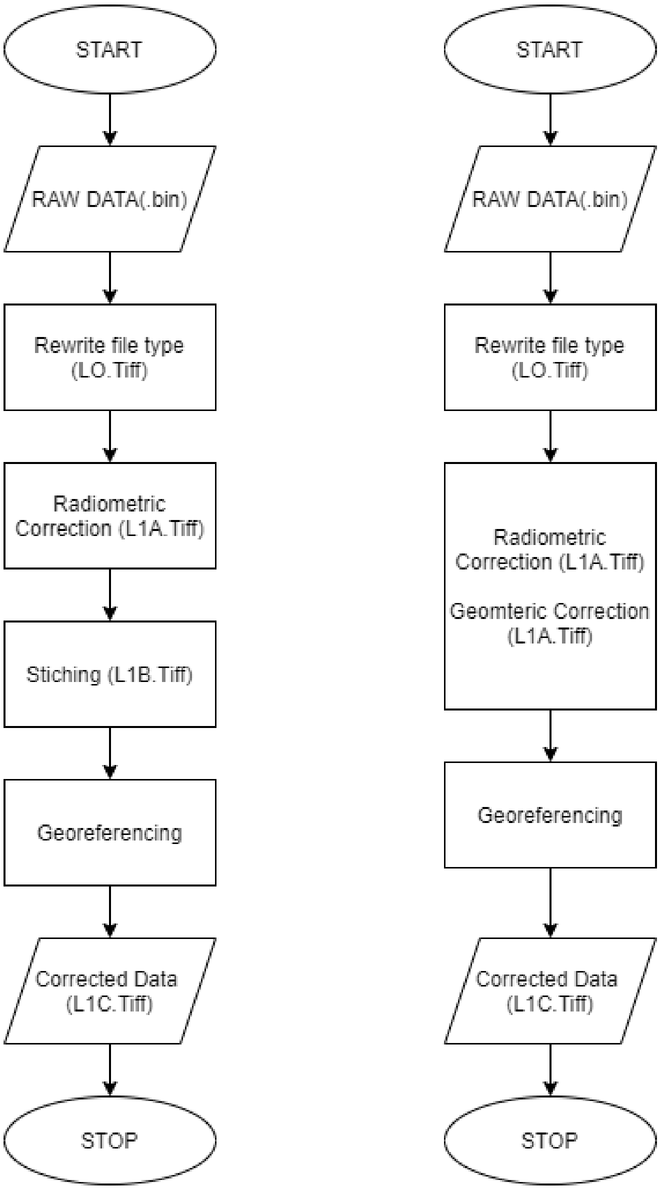

Figure 6.6 LAPAN- Satellite image data processing procedure for digital image (left) and multispectral image (right).

The processing for the image from both LAPAN Satellites is different since each camera has different technical characteristics; hence radiometric & geometric correction applied differently.

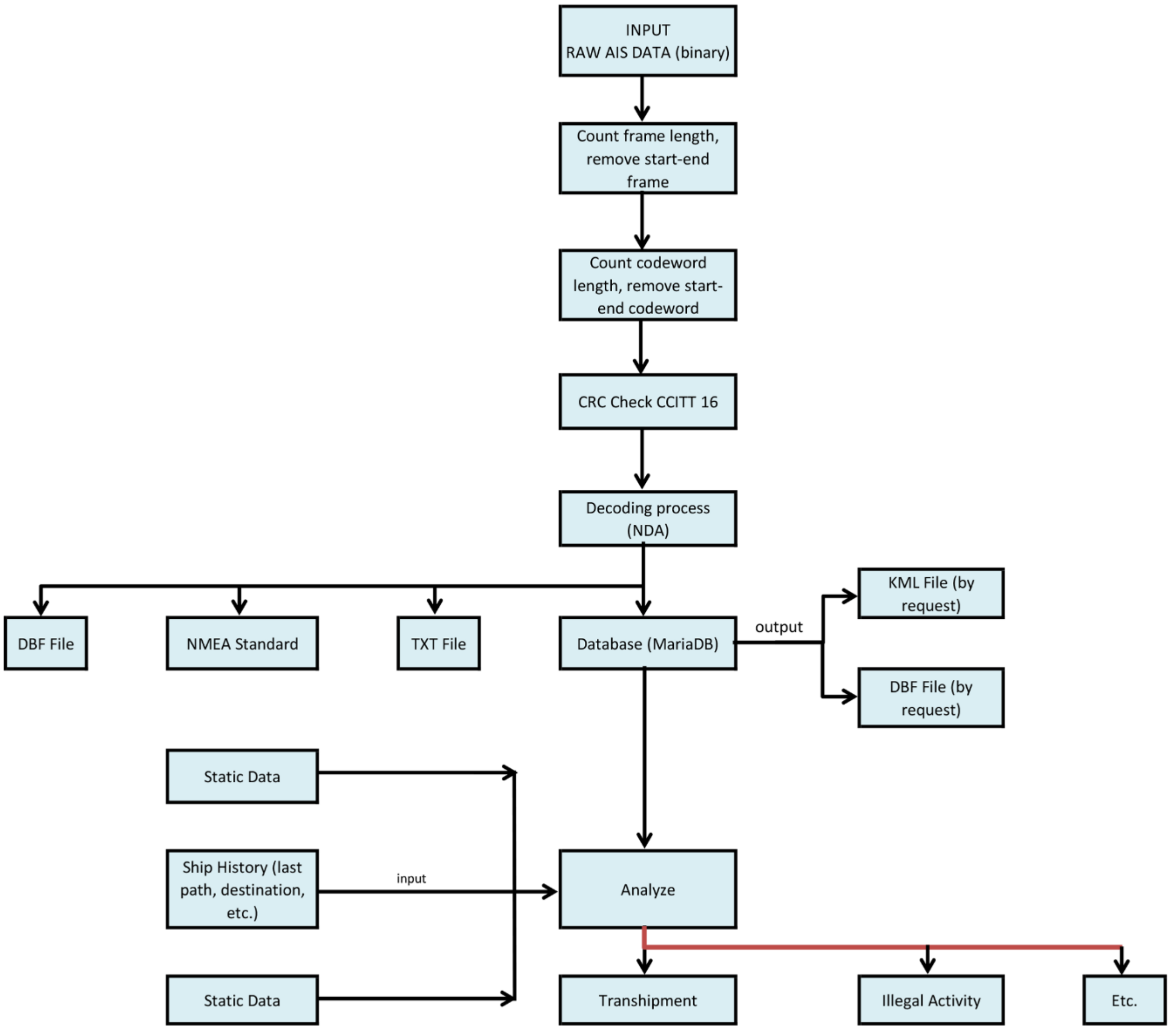

Figure 6.7 LAPAN satellite AIS data processing flow.

Since both satellites also carry AIS receiver payload, there are processing chains as in Figure 6.7 of AIS data received from the satellite. Afterward, an analysis could be done for further added value processing, such as identifying transshipment and other illegal activities. From the flowchart, several output file options are usually requested by the user. The typical file applicable in the maritime application is NMEA standard file. However, the AIS data also could be converted to the database *.dbf file or *.csv file for easy integration into an extensive database system. There is also a possibility to convert the AIS data into *.kml file format that could be integrated directly with the map browser for instant view.

6.2.1 LAPAN-A2 AIS and Digital Camera Payload

In the previous section, it is explained that there are several areas with low AIS density. This low-density AIS area gives a benefit for the high success rate of AIS detection from the satellite. One of the low-density areas is the southern part of Africa. The benefit of AIS surveillance in equatorial orbit with LAPAN-A2 could be seen in Figure 6.8. The figure shows two ships that were waiting in front of the harbor of Mombasa. Those ships are waiting to enter the harbor in free-floating without anchoring from their AIS data due to deep water in that area. From its AIS information, they were drifting to the north and later recovered by its engine and entering the harbor a few hours later. The surveillance of the ship's behavior could be recorded only by continuous monitoring from the satellite. In the case of Mombasa, this behavior could be recorded by the LAPAN-A2 satellite every 90 minutes.

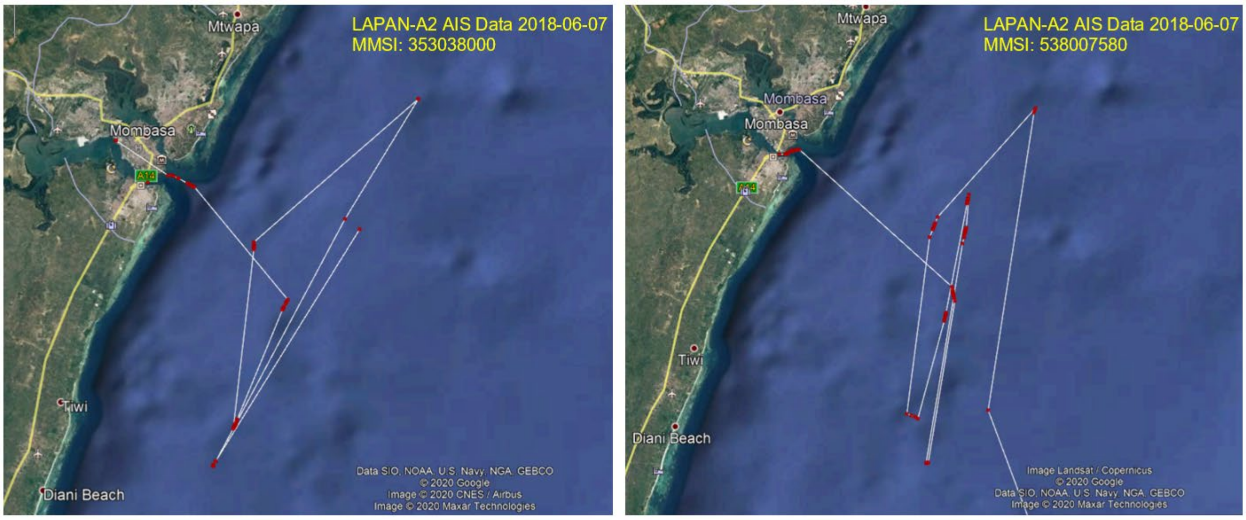

Figure 6.8 Ships free-floating in front of the Mombasa harbor area.

Since LAPAN-A2 satellite orbit cover ± 6 deg latitude, then Mombasa and the ocean surrounding it studied for AIS and its digital image combination. On 17 July 2018, at 11:51 UTC, the LAPAN-A2 satellite could capture the area with 17 frames, covering a total area of 127,4 km x 7,3 km.

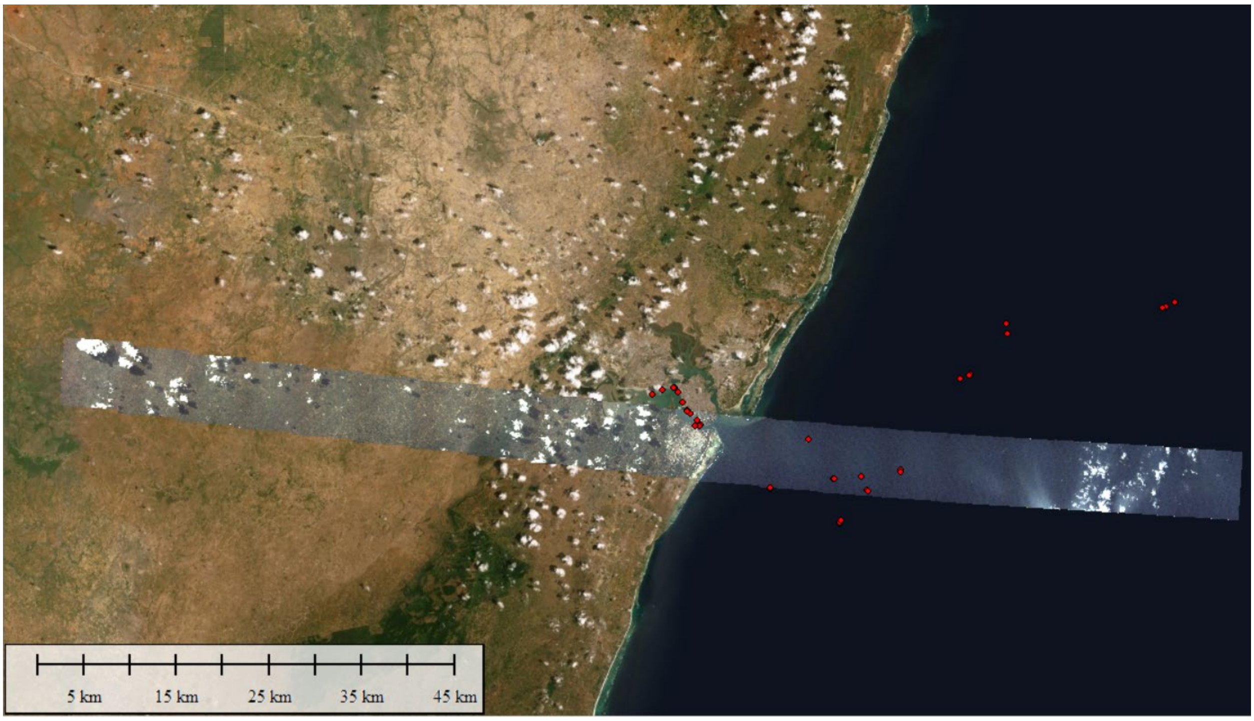

Figure 6.9 Mombasa area captured by LAPAN-A2 on 17 July 2018.

After acquiring the image target area and storage in the satellite memory area, the image is then downloaded in Bogor or Biak Ground Station. Those ground stations capable of receiving S-band downlink with 3 Mbps data rates. After raw image data is received, the Bayer Filter RGB Matrix is implemented to get a full RGB image for each frame [90]. The frame is then combined using a stitching algorithm and further geometrically corrected using a combination of orbital information and known object in the ground. For the geometric correction, worldwide imagery is used as a based map [91], as in Figure 6.9.

In that figure, there are a lot of red dots, which are AIS signal position information. These red dots also locate the ship position. Since some of those AIS signals are located inside the LAPAN-A2 satellite image, it means that the ship could also be identified. Also, some of the AIS signals are located outside of the image from the LAPAN-A2 satellite. The AIS information used in this study was taken from 11:41 UTC to 12:00 UTC.

In this study, the AIS signal that needs to be discussed is the AIS signal located in the open ocean and inside the satellite image, even though several AIS signals are also received from Mombasa's harbor. There are six locations that each ship image might be identified from these criteria, as seen in Figure 6.10.

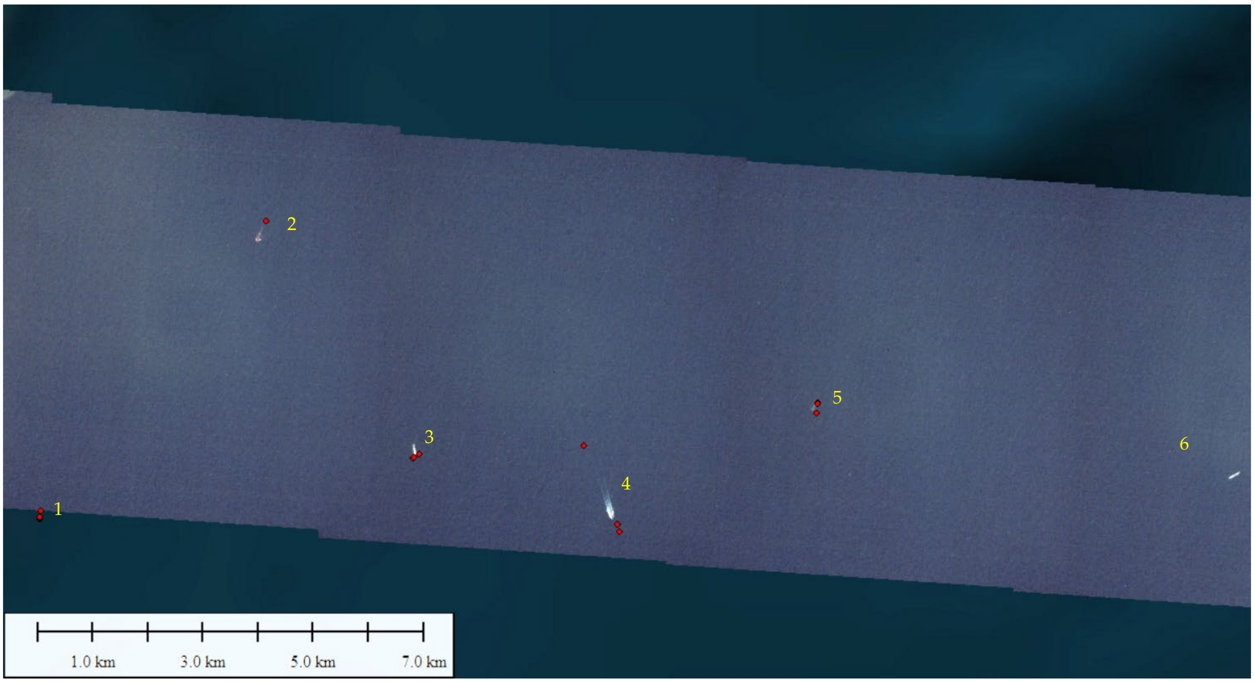

Figure 6.10 Identification of AIS inside LAPAN-A2 image. (17 July 2018)

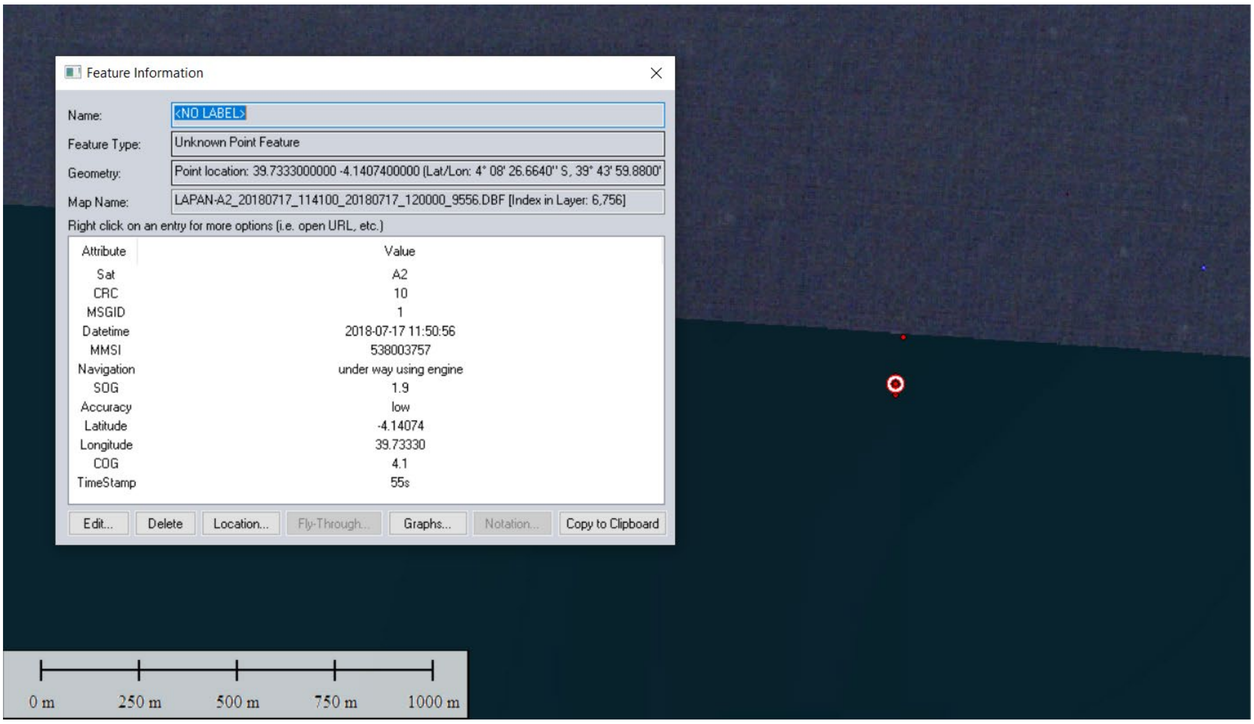

Figure 6.11 Location-1 of AIS identification.

In Figure 6.11, unfortunately, the AIS signal just outside of the image. Hence it is not possible to identify the ship image. However, based on the MMSI database, the ship's name is Olympic Pegasus, with a size of 189.99x32,26 meter. The ship information and ship photos present in this section mostly refer to the information from the website of https://www.vesselfinder.com [92].

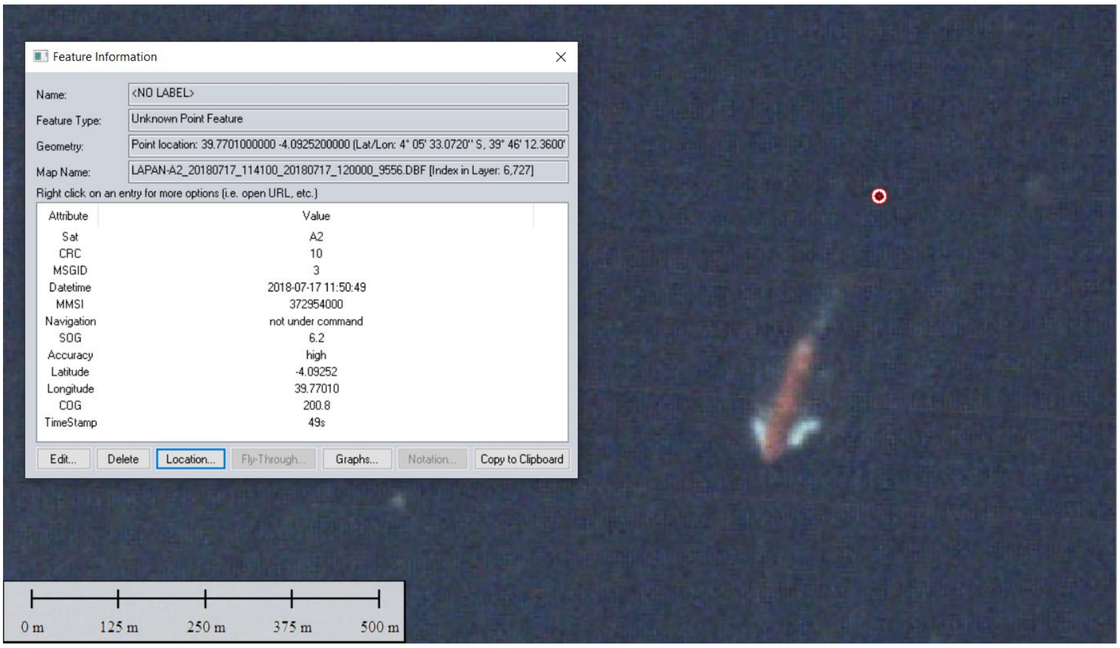

Figure 6.12 Location-2 of AIS identification.

Figure 6.13 Image of the ship in location-2 from the database. *(ship photo by mgklingsick@aol.com via www.vesselfinder.com)*

As in Figure 6.12, we could find a match between a ship image with its AIS signal. The AIS signal also shows the ship course of 200,8 deg, and while looking at the course of the ship in the image also found about 200 deg. As seen from the AIS identification, the ship's MMSI is 372954000 under the name of Torenia. From the LAPAN-A2 image, the color of the ship looks mostly red. By looking at the MMSI database, it could be identified that this is a bulk carrier with a size of 189.99x32.36 meter. The other identification from the ship database shows a matching color of the ship in its image database and image taken from the LAPAN-A2 satellite, as in Figure 6.13 and more detail in Figure 6.14.

Figure 6.14 Detail photo of Torenia ship in location-2. (*ship photo by mgklingsick@aol.com via www.vesselfinder.com*)

In Figure 6.15, the LAPAN-A2 satellite image shows a ship with a dominant white color on the top. Since this image has an AIS signal received by satellite, it found that the ship detected in the satellite image matches the ship image from the database, as in Figure 6.16.

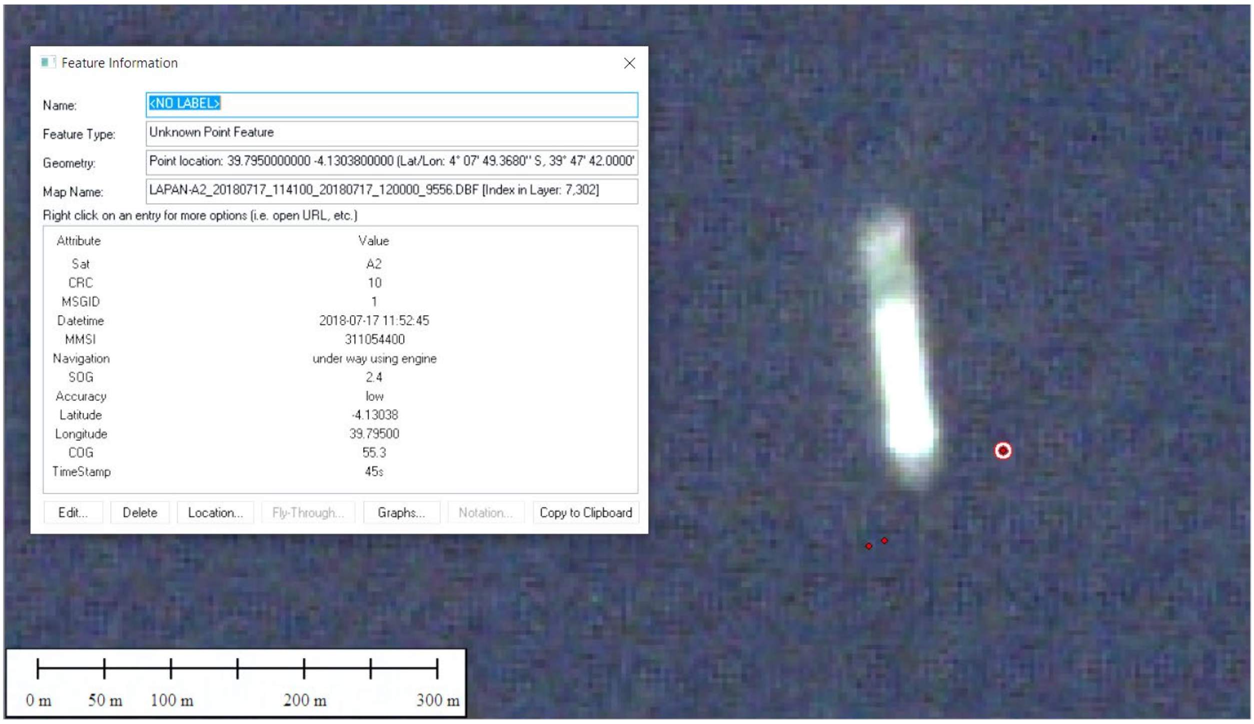

Figure 6.15 Location-3 of AIS identification.

Figure 6.16 Image of the ship (Glovis Clipper) in location-4. *(ship photo by Joseph Kutta via www.vesselfinder.com)*

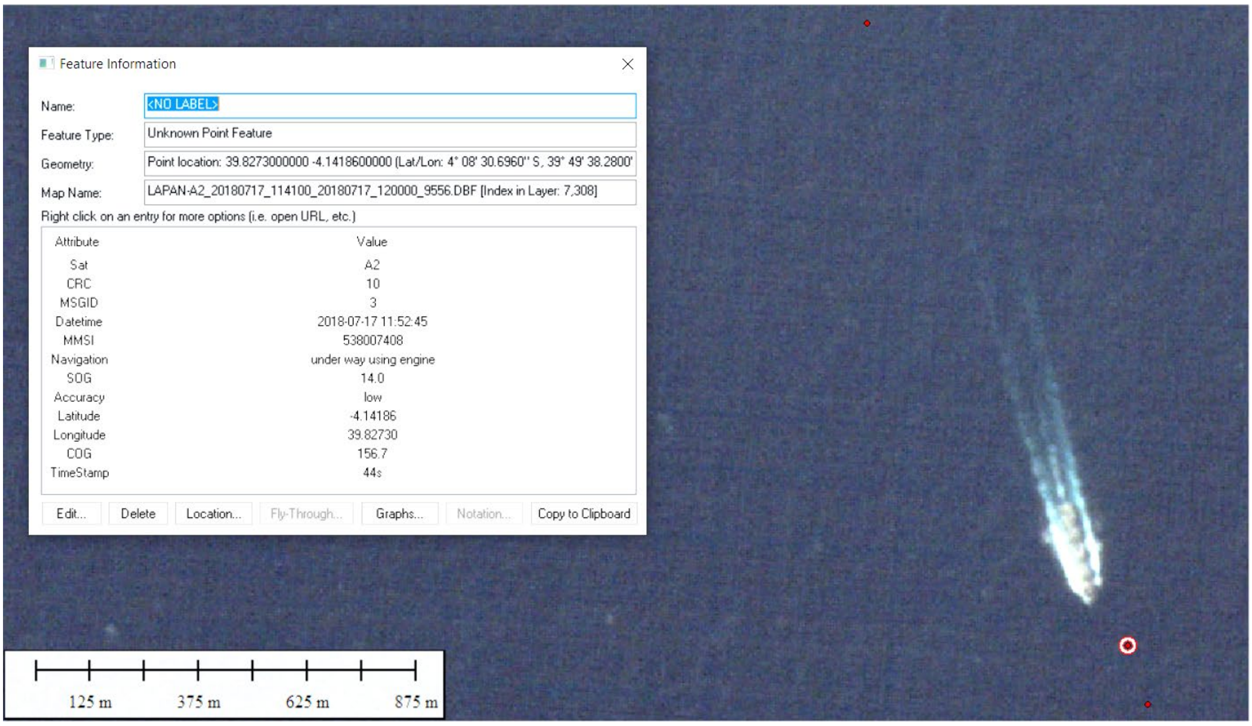

Figure 6.17 Location-4 of AIS identification.

Figure 6.18 Image of the ship in location-4 from the database. (*ship photo by Aart van Bezooijen via www.vesselfinder.com*)

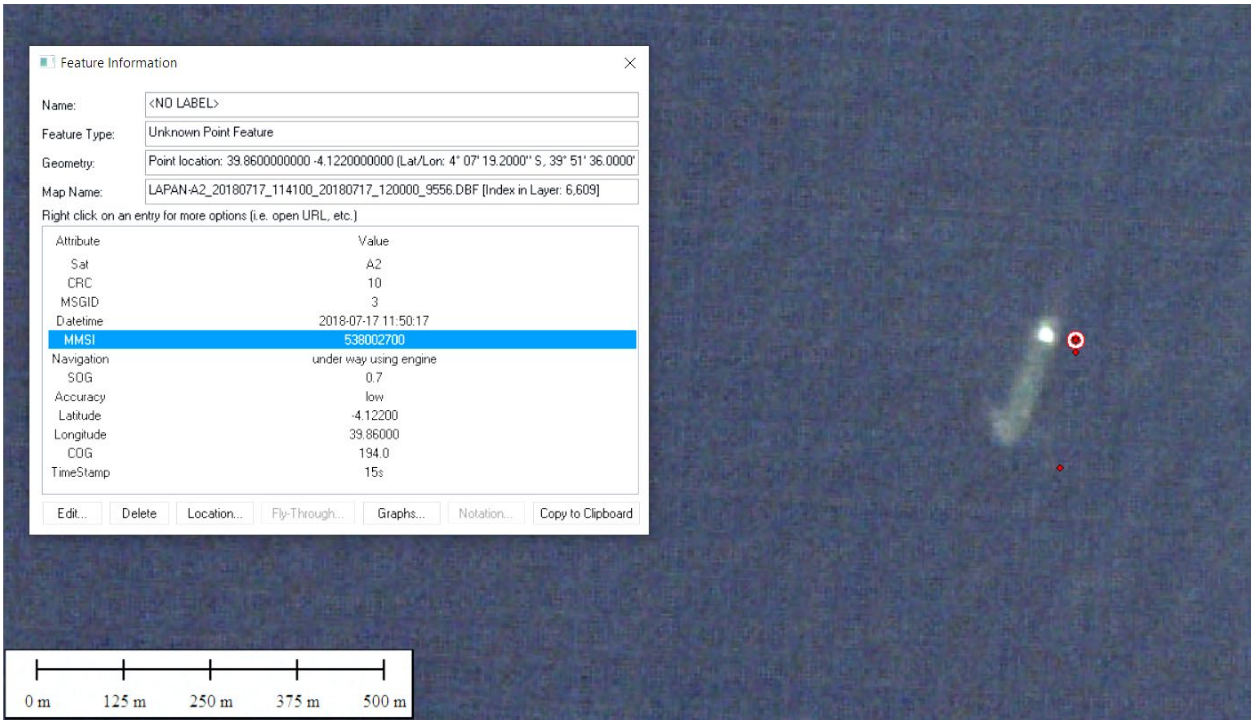

Figure 6.19 Location-5 of AIS identification.

Figure 6.20 Image of the ship (Puze) in location-5. (*ship photo by Miranda Reiffers Teloo via www.vesselfinder.com*)

The matching ship image and AIS information can also be seen in Figure 6.17 and Figure 6.18, also in Figure 6.19 and Figure 6.20. Those images could show that the satellite optical image gives information about the location, course, and size and could especially show the ship’s color, which cannot be seen by the SAR satellite system. In Figure 6.17, even one can see the loading container's shape by looking at the container's shadow on the ship.

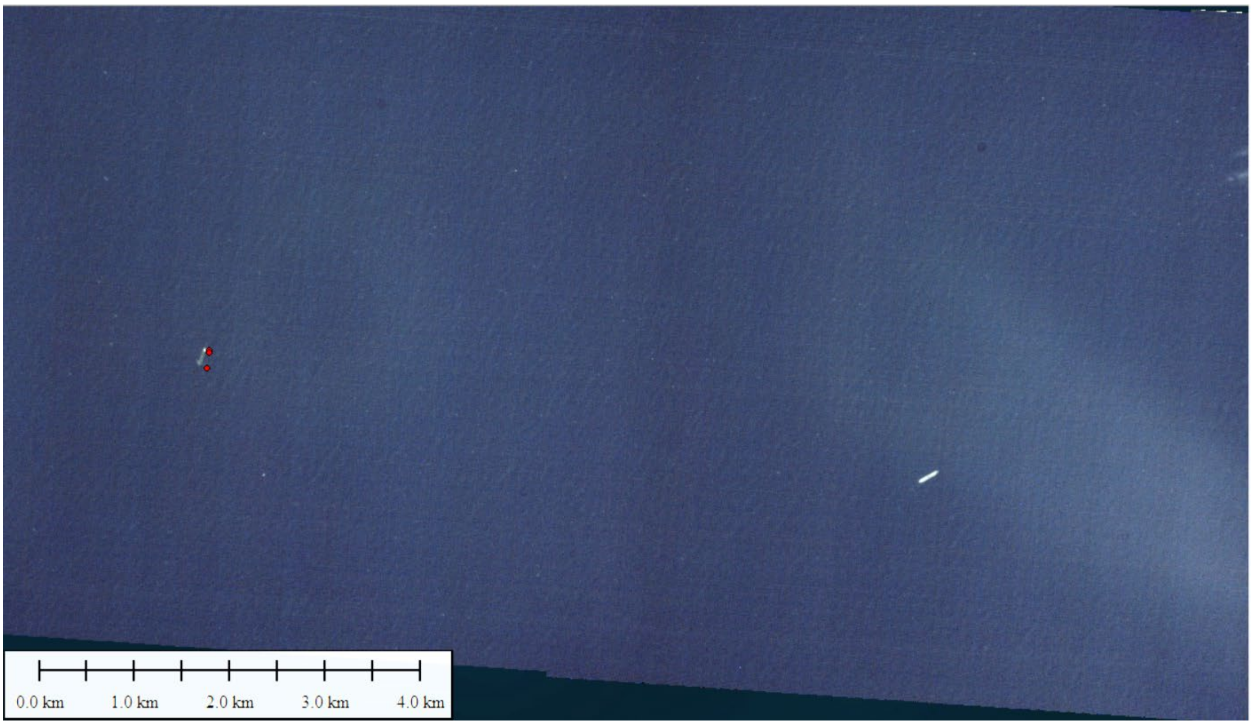

Figure 6.21 Location-6 of ship image.

Figure 6.21 shows a ship image captured by the LAPAN-A2 satellite. However, the AIS signal from this ship could not be received by satellite; hence, it is challenging to find the ship's information. The AIS signal could not be captured by the satellite, perhaps due to the ship's moored position that creates less frequent AIS signal transmission.

However, location and also the size of the ships could be derived from the image. The ship's course is also supposed to be identified from the image; however, it seems that this ship is in a moored position. There is no wave in the image that could be seen, so it is difficult to identify the course. The ship's location could be identified from the image as in a longitude of 39.9277383285 and latitude of -4.1338705337. From the image, the ship's size could be derived as 219-meter length and 30-meter breadth with the course of 59 or 301 deg.

Even though the AIS information could not be derived from the LAPAN-A2 AIS data, the position location and course derived from the satellite image could be used by the maritime authority to analyze further or even further action to see what happen in the area.

From Mombasa's image and AIS acquisition on 17 June 2018 by LAPAN-A2 Satellite, Table 6.1, shows the information of the ships detected in the ocean area surround it.

Table 6.1 Ship information detected by AIS & Image from LAPAN-A2 Satellite (17 July 2018)

Location	1	2	3	4	5	6
AIS & Image Match	No Image (Out of imaging area	Yes	Yes	Yes	Yes	No AIS Info
MMSI	538003757	37295400 0	311054400	538007408	538002700	Unknown
IMO	9545728	9331919	9441582	9436484	9323338	Unknown
Name	Olympic Pegasus	Torenia	Glovis Clipper	GH Scirocco	Puze	Unknown
Vessel Type	Cargo, Bulk Carrier	Cargo, Bulk Carrier	Cargo, Vehicle Carrier	Cargo - Hazard A (Major), Container Ship	Tanker, Oil/Chemica l Tanker	Unknown
Call Sign	V7SZ6	3ELI5	C6ZE8	V7MH3	V7KY8	Unknown
Flag	Marshall Island	Panama	Bahamas	Marshall Island	Marshall Island	Unknown
Gross Tonnage (Tonne)	32983	31236	58767	36007	30641	Unknown
Length & Breadth size (m)	189.99 & 32.26	189.99 & 32.26	199.99 & 32.29	230.95 & 32.29	195.3 & 32.24	219 & 30 (Estimated)
Year Built	2011	2007	2012	2009	2006	Unknown

Since on 18 July 2018, the orbit of the LAPAN-A2 Satellite also still near the Mombasa area, another attempt has been made with less cloud in the area at 12.14 UTC, as seen in Figure 6.22 and more detail in Figure 6.23.

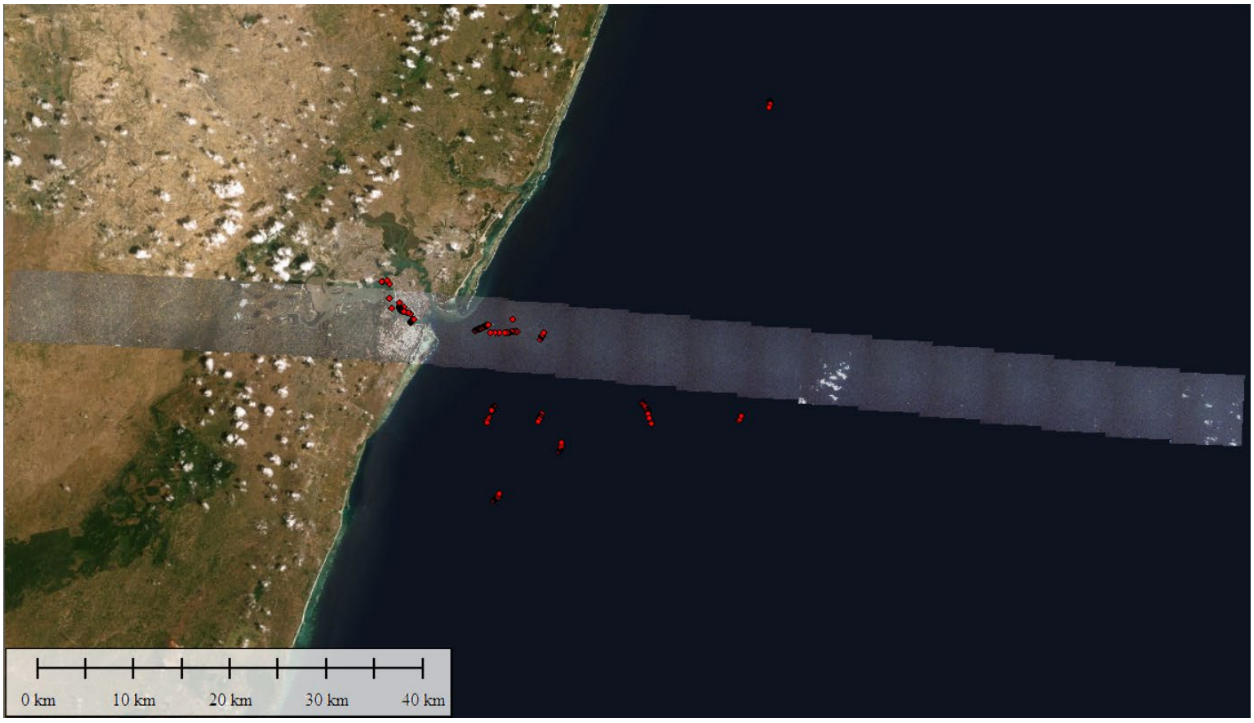

Figure 6.22 Mombasa area captured by LAPAN-A2 on 18 July 2018.

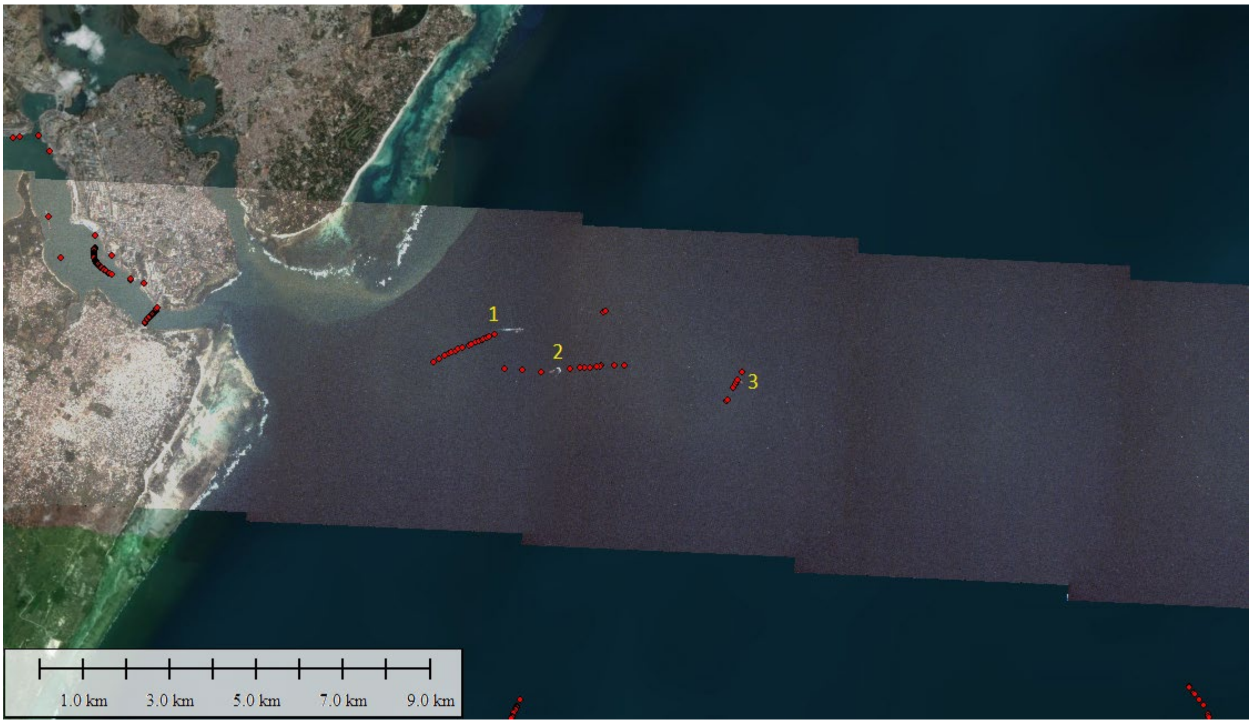

Figure 6.23 Identification of AIS inside LAPAN-A2 image. (18 July 2018).

Figure 6.24 shows a ship underway by looking to its wave in the back. In the database, this is a cargo ship, and the different colors of the container also could be seen. From the ship information, the satellite image also matches the ship image, as shown in Figure 6.25. In Figure 6.24, AIS information is sent by the ship almost every 10 seconds since the speed of the ship is 12.8 knots.

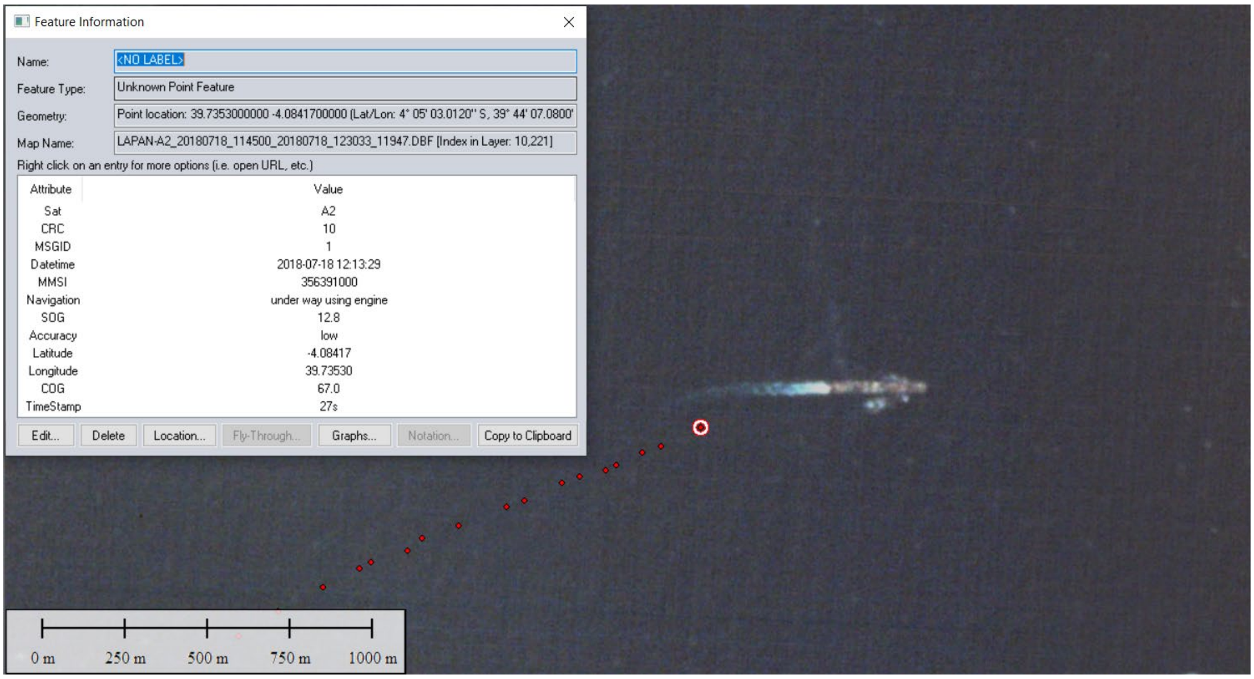

Figure 6.24 Location-1 of AIS identification. (18 July 2018)

Figure 6.25 Image of the ship in location-1. (*ship photo by Aart van Bezooijen via www.vesselfinder.com*)

In the location-2, LAPAN-A2 could identify a ship that also underway with a speed of 8 knots, as in Figure 6.26. This ship picture shows that this is a cargo container ship, as shown in Figure 6.27.

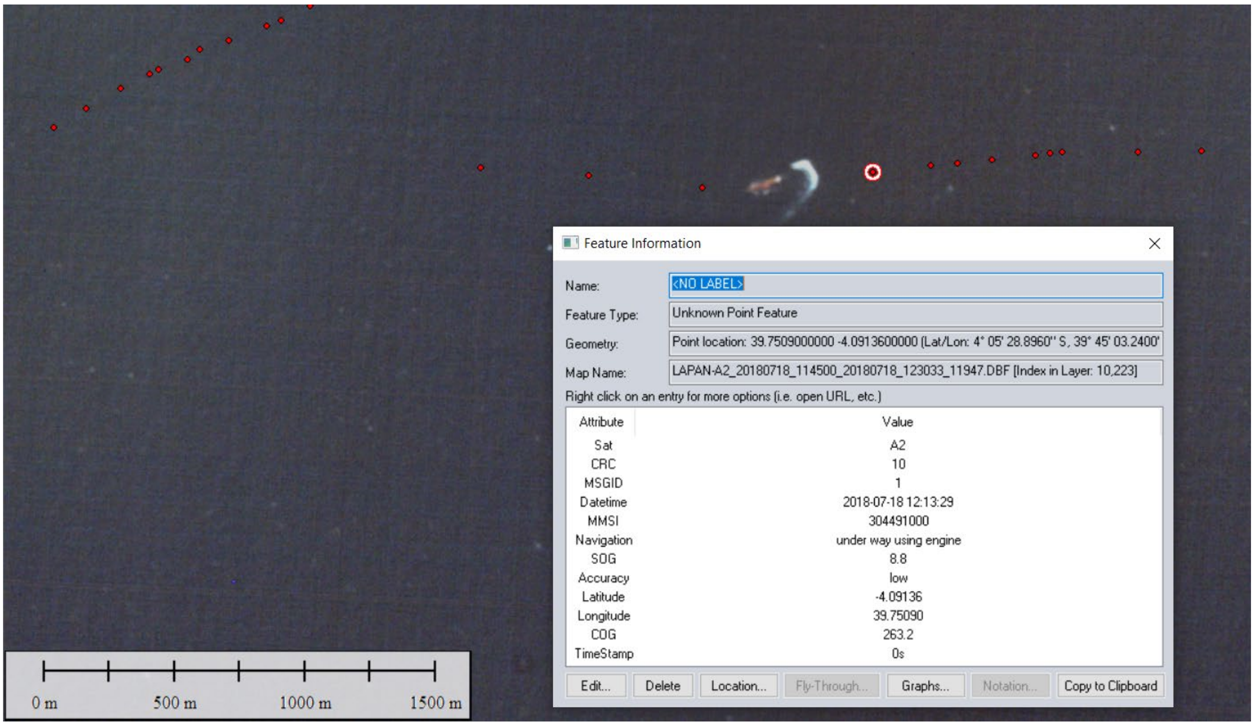

Figure 6.26 Location-2 of AIS identification. (18 July 2018)

Figure 6.27 Image of the ship in location-2. (*ship photo by Manuel Hernández via www.vesselfinder.com*)

In the third location, as in Figure 6.28, it also found a ship that matches its picture as one could see the white color in the back of the ship the same as the ship bridge in the picture, as in Figure 6.29. However, it is interesting that the ship's heading is looking at the angle of ~134 deg while the AIS information shows the ship's course is about 26 deg while there is no back wave seen in the image. The AIS information also shows that the ship was moving at the speed of more than 3 knots. This ship also sent its AIS in about every 10 seconds. This frequent transmission could be understood since a ship at anchor or moored and moving faster than 3 knots should transmit its AIS every 10 seconds.

From the different information from AIS and the image gathered, the forward ship engine is not running even though the AIS status shows that it is underway. Since the forward engine stops without anchoring, so the strong sea wave or wind drift the ship more than 3 knots to the side, as shown in AIS information. During the imaging, the wind information gathers also shows that the wind direction was coming from south to southwest direction with 28 km/h [93], which is the same as the drift direction. Another possibility why the AIS information shows that side drift is that the ship runs its side propeller. However, this might not happen since the ship was in the open ocean, and perhaps no maneuvering using a side propeller is needed.

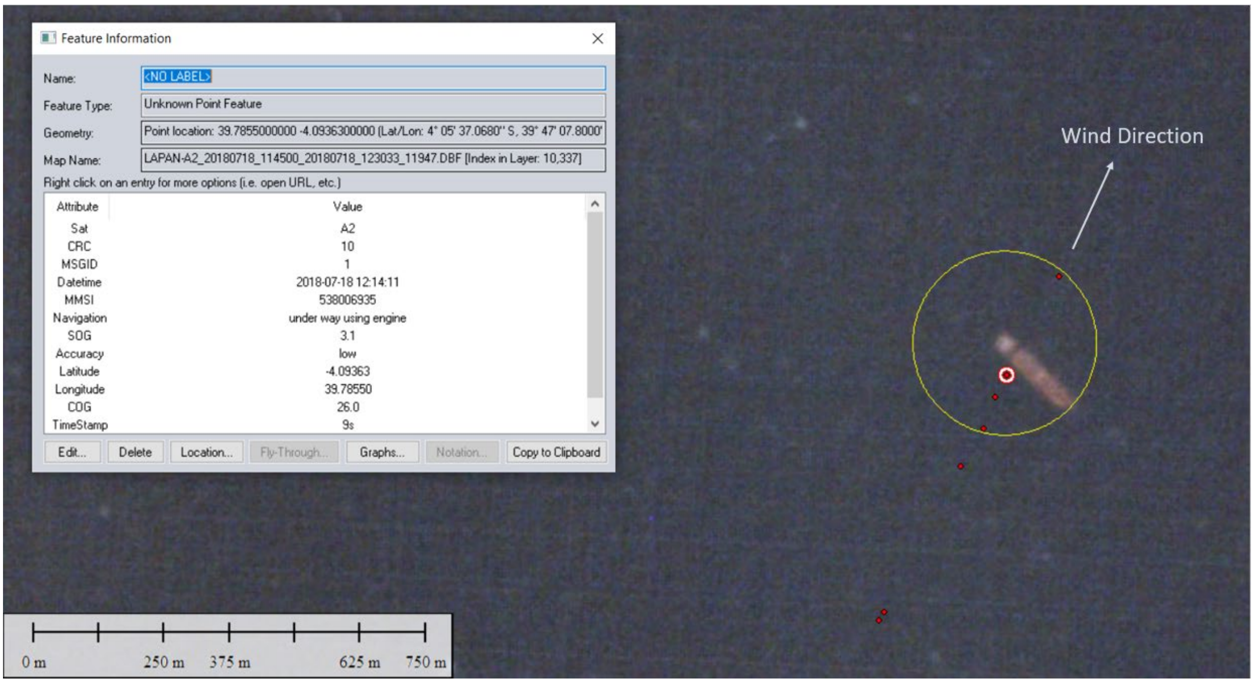

Figure 6.28 Location-3 of AIS identification. (18 July 2018)

Figure 6.29 Image of the ship in location-3. (*ship photo by Miranda Reiffers Teloo via www.vesselfinder.com*)

The Mombasa image taken on 18 July 2018 shows at least three ships could be imaged and match with its AIS information, as shown in Table 6.2.

Table 6.2 Ship information detected by AIS & Image from LAPAN-A2 Satellite (18 July 2018)

Location	1	2	3
AIS & Image Match	Yes	Yes	Yes
MMSI	356391000	304491000	538006935
IMO	9142174	9175717	9490820
Name	Ever Develop	RENO	Wilton
Vessel Type	Cargo, Container	Cargo, Container	Cargo, Bulk Carrier
Call Sign	3FLF8	V2BC5	V7RY8
Flag	Panama	Antiqua Barbuda	Marshall Island
Gross Tonnage (Tonne)	52090	12827	32839
Length & Breadth size (m)	294.13 x 32.22	153.6 x 25.29	189.99 x 32.26
Year Built	1998	2000	2011

In the Mombasa image on 18 July 2018, as shown in Figure 6.30, at least eight ships with AIS information could be received by the LAPAN-A2 satellite. From those ships, two ships were moving in the harbor. This image also shows that more ships could be seen from the image. One of the big ships that could be seen is a ship transmit its AIS data (circled). This ship is a crude oil tanker with an MMSI of 636011643, as in Figure 6.31. However, behind that ship, one big ship did not transmit its AIS data, or perhaps its AIS data could not be received by satellite.

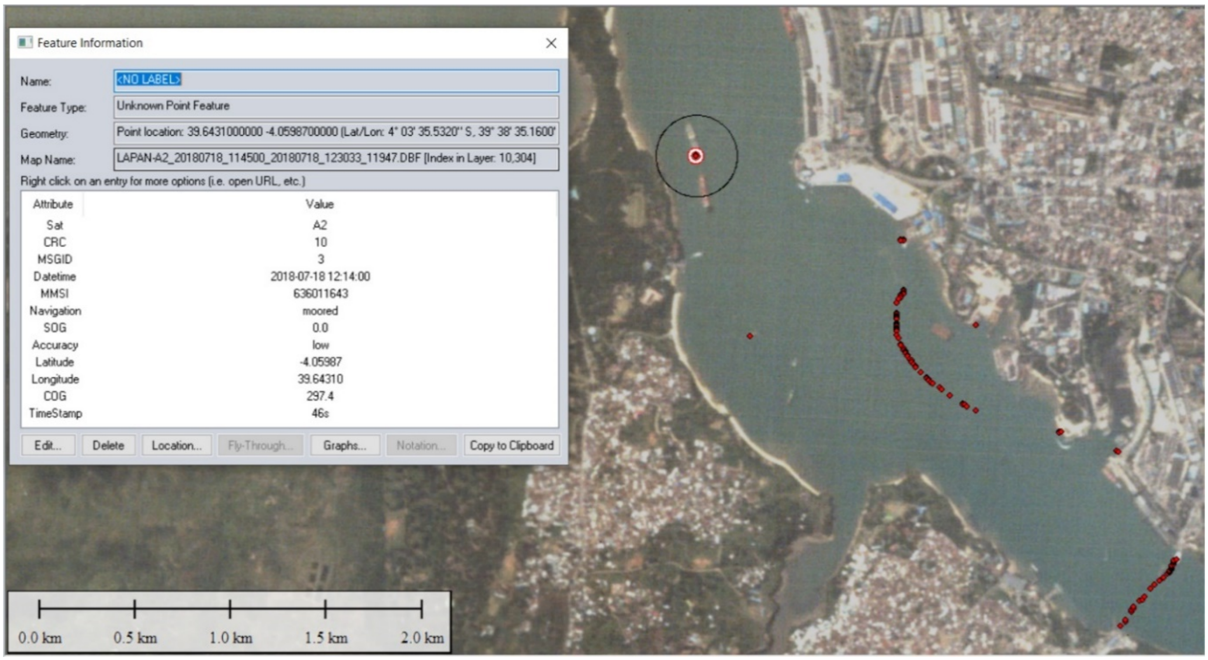

Figure 6.30 Ship in Mombasa harbor.

Figure 6.31 Picture of a ship in Mombasa harbor. (*ship photo by Jan van der Pluijm via www.vesselfinder.com*)

6.2.2 LAPAN-A3 AIS and Multispectral Camera Payload

As described in the previous section, LAPAN-A3 also carries a digital and multispectral camera and an AIS receiver payload. Figure 6.32 shows the general mapping strategy used for the LAPAN-A3 satellite operation. This mapping strategy is applied to the area that will be captured. Prior to that imaging time, the satellite attitude must be set. The satellite attitude is controlled by using the momentum bias method in which the angular momentum is maintained on the Y-axis. The Y-axis is defined as the pitch axis, which is perpendicular to the flight direction. Since the satellite mapping strategy only requires the satellite to be able to adjust the attitude in the roll axis, every imaging schedule can be accomplished by setting actuator-coil in Y-axis for certain values for a certain period before imaging time [94].

The smooth attitude control during imaging is required to ensure the multispectral image data could be adequately corrected [95]. To accomplish the mission, LAPAN-A3 satellite uses momentum biased attitude control by using magnetic torque to control the angular momentum vector and a reaction wheel to spin the satellite to remain nadir. However, based on the observation during the satellite spinning, there are nutation and precession, which occurred with 0.28° amplitude and 73 seconds period, and precession was observed with a 1° amplitude and 92 minutes period. This nutation and precession profile lead 2.6° attitude accuracy and maximum movement on ground track 0.055 km/s in along-track direction and 0.259 km/s (0.026°/s) in the cross-track direction. Both attitude accuracy and movement have outperformed the limitation [96].

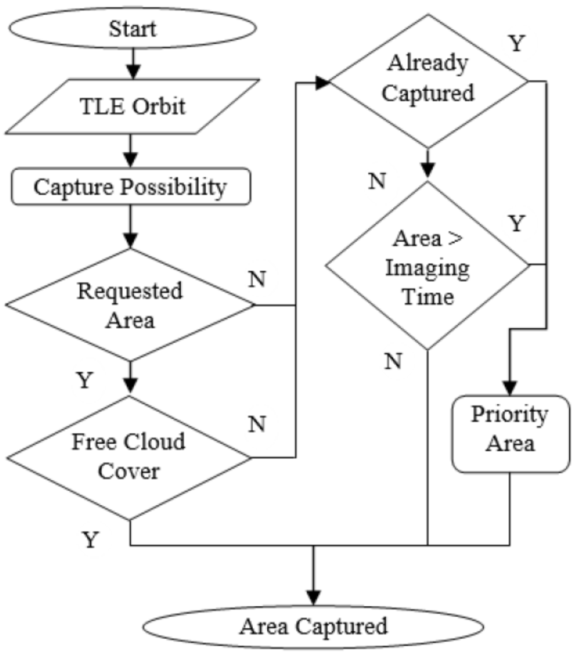

Figure 6.32 Flowchart of LAPAN-A3 mapping strategy [94]

The digital camera in LAPAN-A3 is the same specification as the LAPAN-A2 satellite, so the discussion focuses on a multispectral image combination with its AIS reception. The multispectral image of LAPAN-A3 has the advantage of the wider swath, and also its multispectral characteristic could be used for ship identification. However, due to its medium resolution of 16 meters, it is difficult to see ship color features and the ship's precise dimension.

The multispectral image from LAPAN-A3 has a misalignment between each line Figure 6.33. This misalignment happens due to the CCD line sensor's mechanical separation. This misalignment has been systematically corrected by developing a band co-registration modeling, vignetting correction before the image delivers to the user [52] [97]. During the LAPAN-A3 multispectral imager operation, vicarious calibration has been conducted to see if there is a degradation of the camera's radiometric parameter, and a new calibration parameter is needed [51].

Figure 6.33 Misalignment of each CCD channel of LAPAN-A3 Satellite; uncorrected (left) and corrected (right). (adapted from [52])

As shown in the previous chapter's density map, the sea around South Africa and its southern Atlantic are among the less ship density areas. With the less density ship, it is suspected that the AIS signal from the ship is easily received by satellite. For the same reason of less cloud and less crowded ship, the study of the combination of multispectral and AIS is done in the African continent. As Figure 6.34 shows, Cape town city and sea areas surround it. This image of 350 km x 120 km was taken on 7 September 2019 from 07:48:40-07:50:13 UTC (294 seconds) by the LAPAN-A3 satellite.

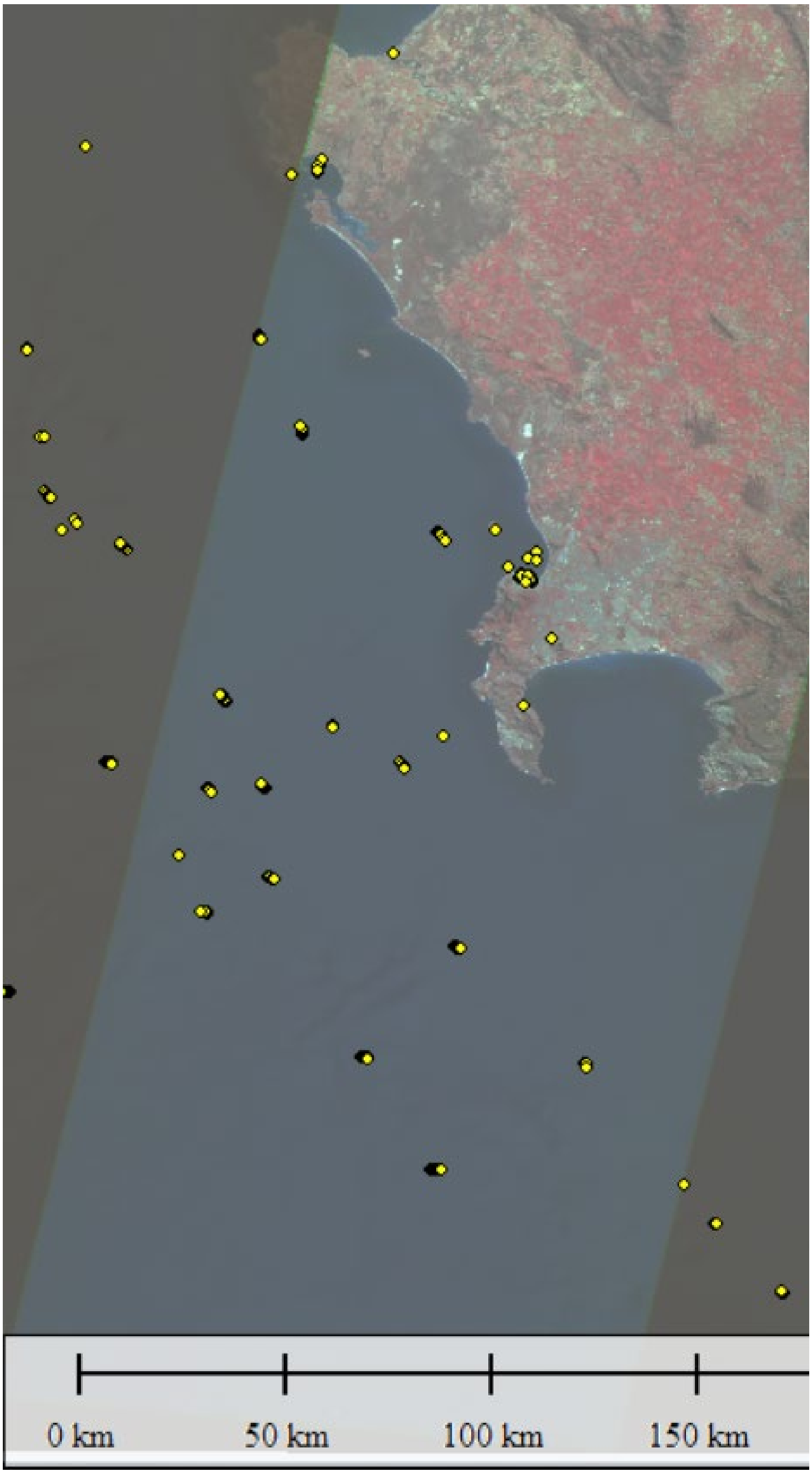

Figure 6.34 Image of Cape Town captured by LAPAN-A3 Satellite on 7 September 2019.

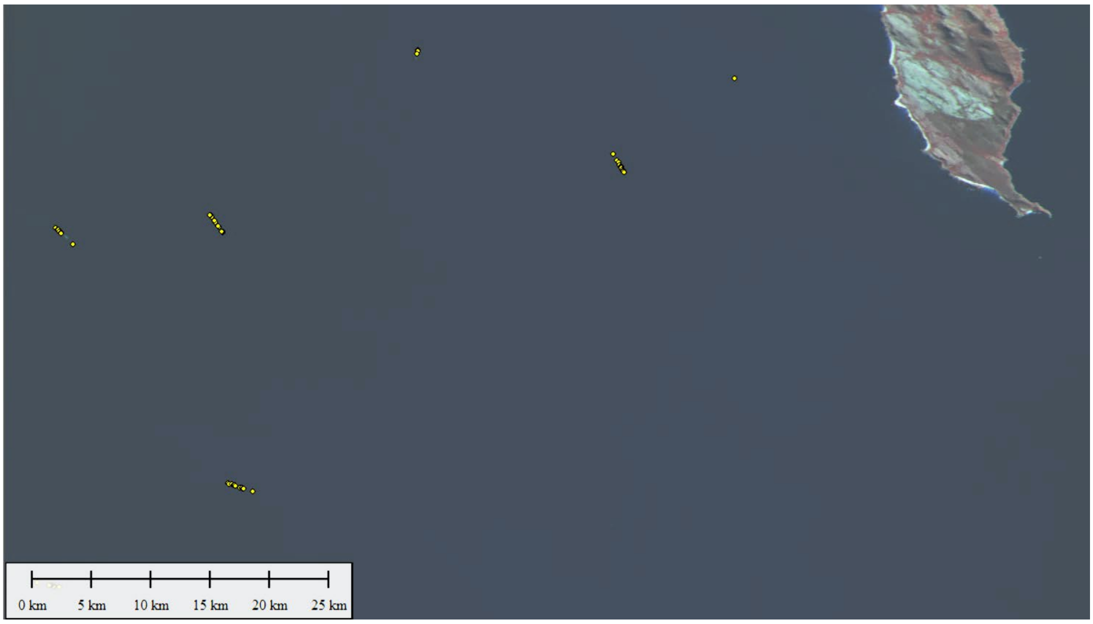

Figure 6.35 Several ship activities in Cape Town.

Figure 6.35 shows some ship activities around the cape town ocean. Several ships underway could be identified from the AIS footprint while some other ship was moving at low speed or moored.

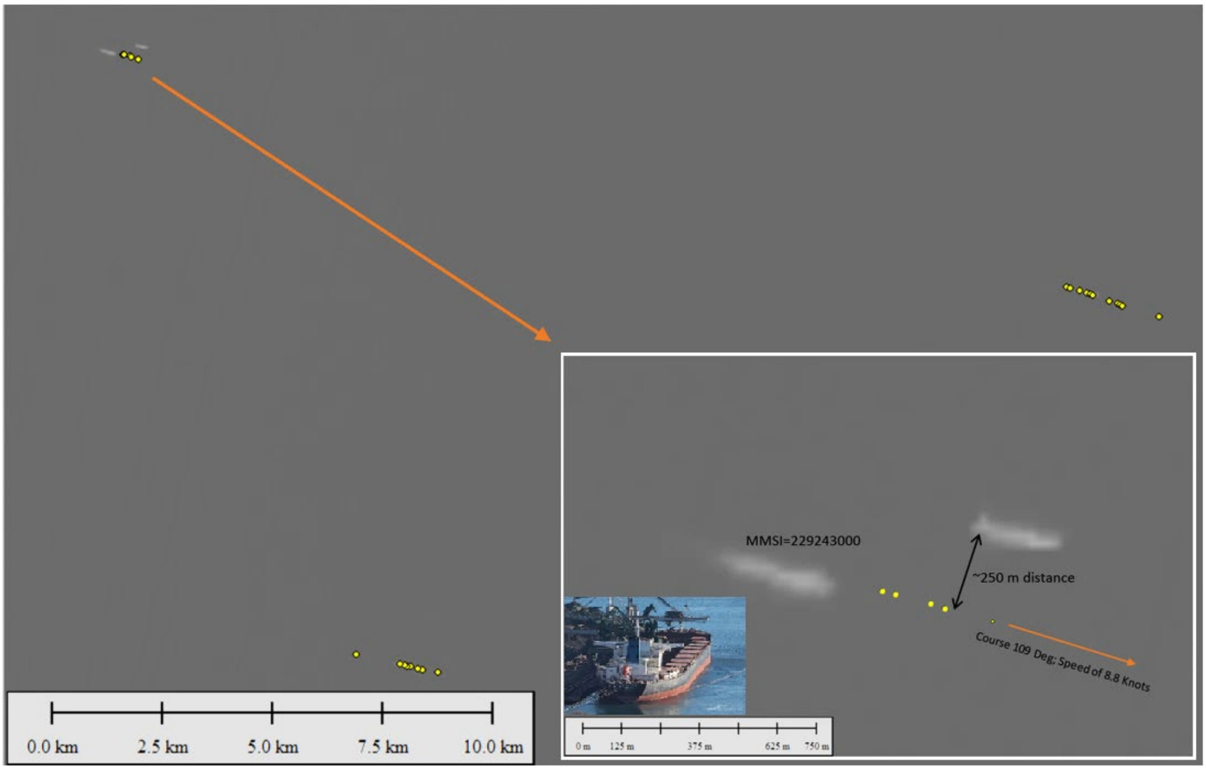

Figure 6.36 A ship with MMSI 229243000 underway near a ship with no AIS information. (*ship photo by Dragec via www.vesselfinder.com*)

Figure 6.36 shows a cargo ship with MMSI 229243000 underway with 8.8 knots with a course of 109 deg near an object that should be an unidentified ship with ~200-meter length. Strangely, this unidentified ship did not transmit its AIS, while the reception from the satellite for the other two ships nearby, as shown in the picture, is acceptable. The no transmission of AIS of a ship in the open ocean indicated that some problems might happen. In low visibility due to bad weather, no AIS transmission from a ship could be a danger to another ship since a collision may happen between the ships. By looking at the picture, it could be seen that the ship with MMSI 229243000 only has around 250 meters separation from the unidentified ship, which quite close. This case is one of the importance of ship surveillance with optical satellites.

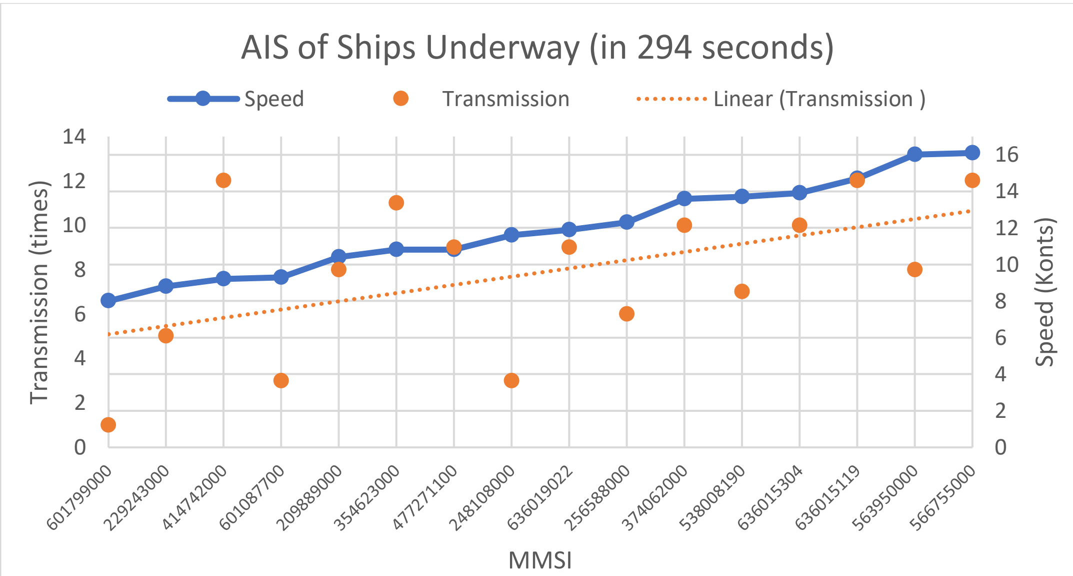

Figure 6.37 AIS of ships underway.

Figure 6.37 shows 16 ships underway with more than 8 knots. From the figure, it could be seen that the more speed a ship is moving, the AIS information should be sent more frequently, up to 2 seconds by that ship, according to Table 2.2 in the previous section. The more frequent AIS is transmitted, then it has more probability to be received by satellite. Within 294 seconds, the ships that travel more than 14 knots should transmit 49 times (every 2 seconds) AIS information. However, the ships that travel between 0-14 knots should transmit 29 times (every 10 seconds) during the acquisition time. From this assumption, then the average reception of the AIS satellite is around 24%, with the reception percentage varies from 3 to 37%, which depends on several factors discussed.

On the other hand, there are 30 ships and three base stations (MMSI with seven digits) shows at low speed or even 0 knots, as shown in Figure 6.38. The figure also shows that there are ships at low speed but still transmit its AIS quite frequently. According to Table 2.2, the ships in moored/anchor status sent the AIS every 3 minutes. However, this is not applicable for a ship that is not in moored or anchor even its speed is 0 knots or slow maneuver. The ship, which has 0 knots without moored/anchor and maneuver, should transmit its AIS every 10 seconds. This is why several ships, i.e., a big ship with MMSI no. 636018475 with a speed of 0,2 knots and AIS, transmitted its AIS 7 times within 294 seconds since this ship changing its course from 14 deg to 257 deg. Another interesting example is a fishing boat that has the status of engaged in fishing with MMSI 431725000, which has 0 knots of speed; however, its AIS is captured by satellite 14 times within 294 seconds.

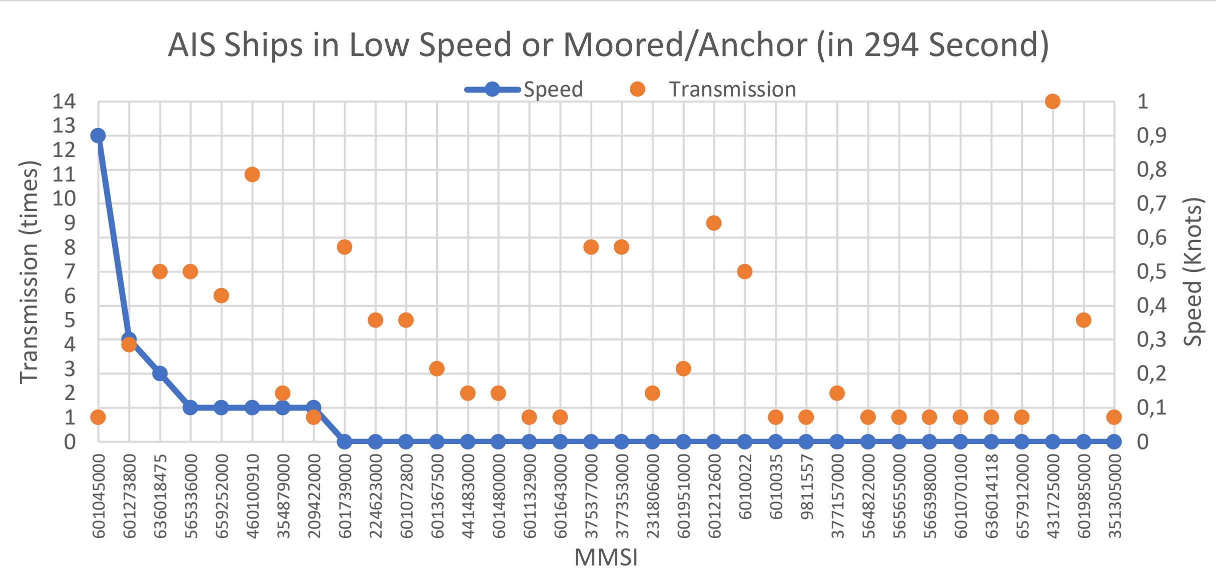

Figure 6.38 AIS of ships at low speed or moored/anchor.

The AIS information received by LAPAN-A3 satellites shows the dynamic of AIS information sent by those ships, and this information useful for activity surveillance of those ships. This AIS surveillance could be combined with a multispectral image from the LAPAN-A3 satellite.

However, as mentioned previously, due to the medium resolution of the camera and characteristic of its spectral band, it is essential to identify which spectral band suited to be used to identify the ship. This identification is also essential to reduce the image processing complexity used to identify a ship within the medium resolution.

Figure 6.39 A typical image of the big ship in each spectrum detected by LAPAN-A3 multispectral. (ship photo from http://www.shipspotting.com/gallery/photo.php?lid=1971908)

Figure 6.39 shows a ship Maersk Line with a size of 249.12 x 37.4 m captured by the LAPAN-A3 multispectral imager. The figure shows that the spectral red and green are clearer to see the type of ship's size in a medium resolution image.

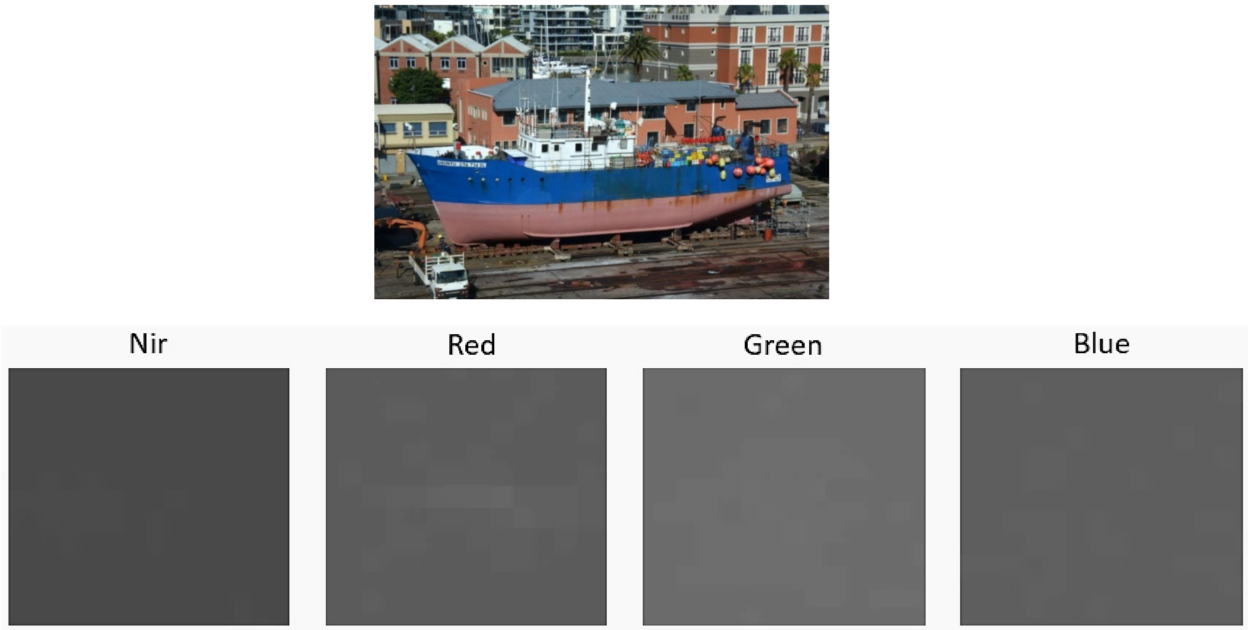

Figure 6.40 A typical image of the small fishing ship in each spectrum detected by LAPAN-A3 multispectral. (ship photo from http://www.shipspotting.com/gallery/photo.php?lid=2872843)

However, for a small ship, i.e., fishing boat with a size of 27.73 x 6.43 m, as shown in Figure 6.40, the red channel is the only clearer image for that ship. This small ship's size is difficult to see since the image's pixel size only becomes 1.7 x 0.4-pixel size. Based on this result, it is better to use only a red channel to find the ship in the image, especially for small ships, for multispectral images. The use of a single-channel for finding ships also eliminates confusion due to the multispectral sensor's miss-alignment.

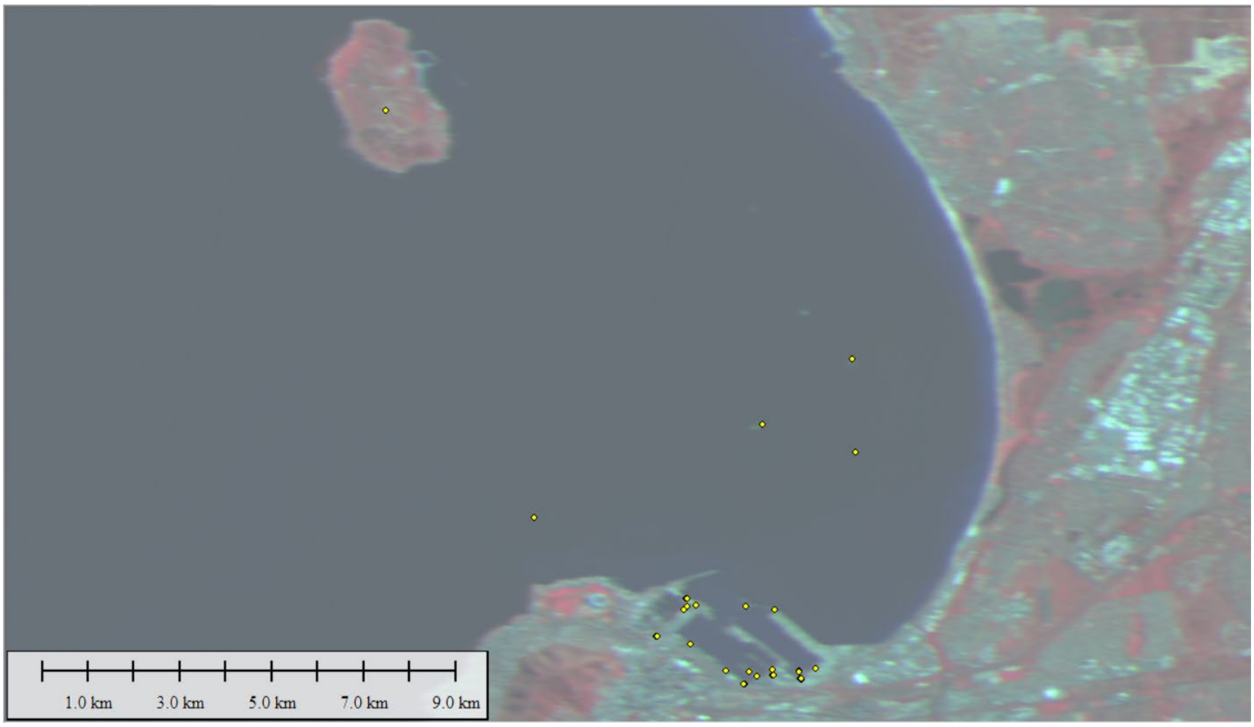

Figure 6.41 AIS signal in the harbor of Cape Town & surround the area.

Figure 6.41 shows several AIS signals coming from several ships around the harbor. There is also a terrestrial AIS transmitted from Robben Island.

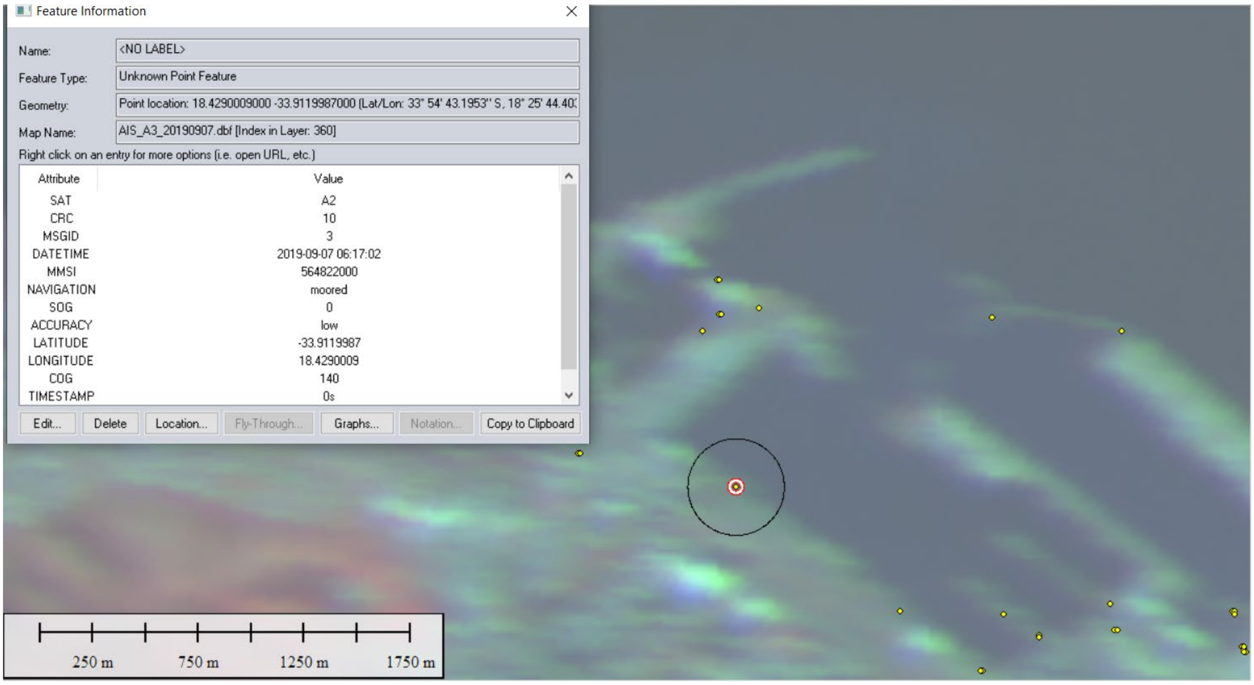

Figure 6.42 AIS Signal in the harbor of Cape Town.

Figure 6.42 shows several AIS signals in the harbor. However, it is impossible to distinguish the harbor's details due to its medium resolution, even for identifying a big ship, as its AIS is detected by the satellite in the image. The AIS sample detected in the harbor is the ship with an MMSI of 564822000 under the name of Maersk Varna with a size of 179.65 x 27.64 m.

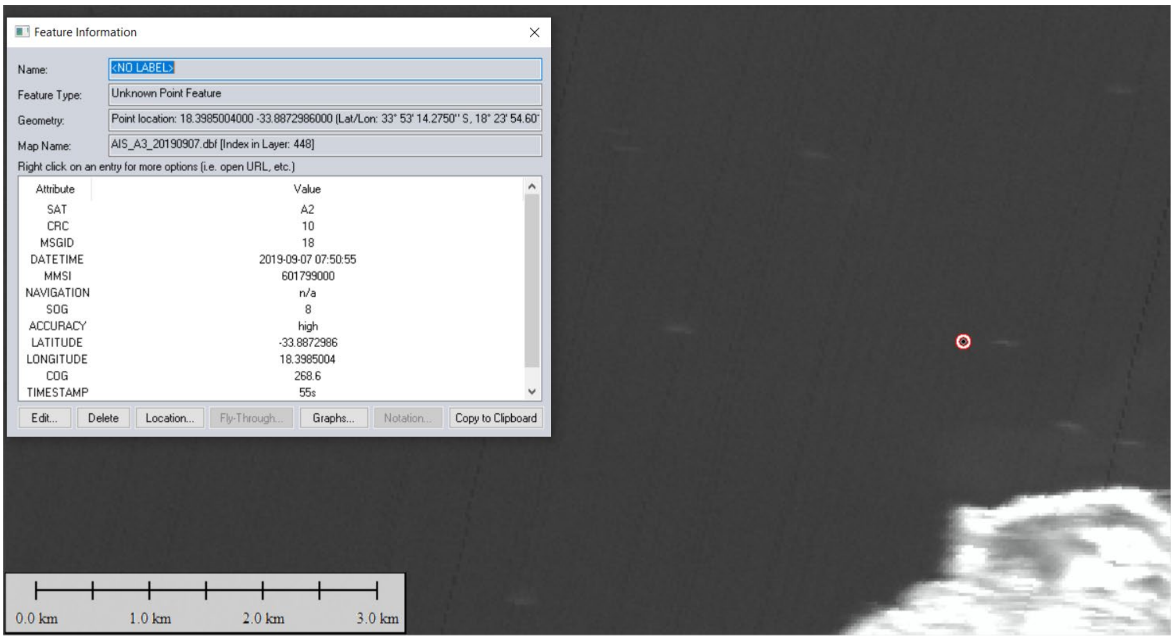

Figure 6.43 AIS of a fishing boat near Cape Town harbor.

Another sample of a small fishing boat shows in Figure 6.43. In this image, its AIS location and the image of the ship separated about 270 m. This different position happen since imaging of the ship happens 1 minute before its AIS is transmitted. From the AIS information, it could be seen that the boat moves in the direction of 268 degrees with a speed of 8 knots. From the ship's database, it is known that the ship size is 27.73 x 6.43 m and its picture, as shown in Figure 6.40. This small size creates an image of the ship taken from the satellite is challenging to be identified.

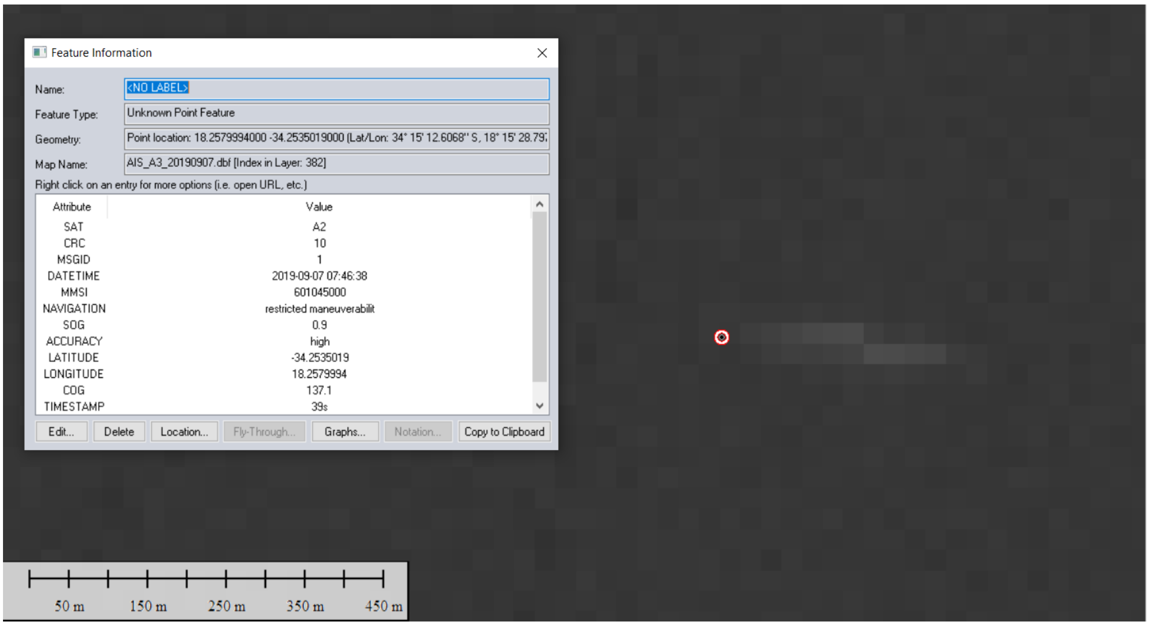

Figure 6.44 Another sample of a fishing boat with its AIS in the ocean.

Figure 6.44 shows the vessel RS ALGOA (MMSI: 601045000) is a Fishery Research Vessel that was built in 1975, and it is sailing under the flag of South Africa with a size of 52.55 x 10.8 m. Same as the previous figures, the ship details are challenging to be seen in the image of a medium resolution image, even though the direction still could be identified.

For large ship sample detected by LAPAN-A3 multispectral could be seen in Figure 6.45. From the database, this is a tanker ship named Spyros k with a size of 274.27 x 48.04 m. This size of a big ship could be identified in the image by using a medium resolution image.

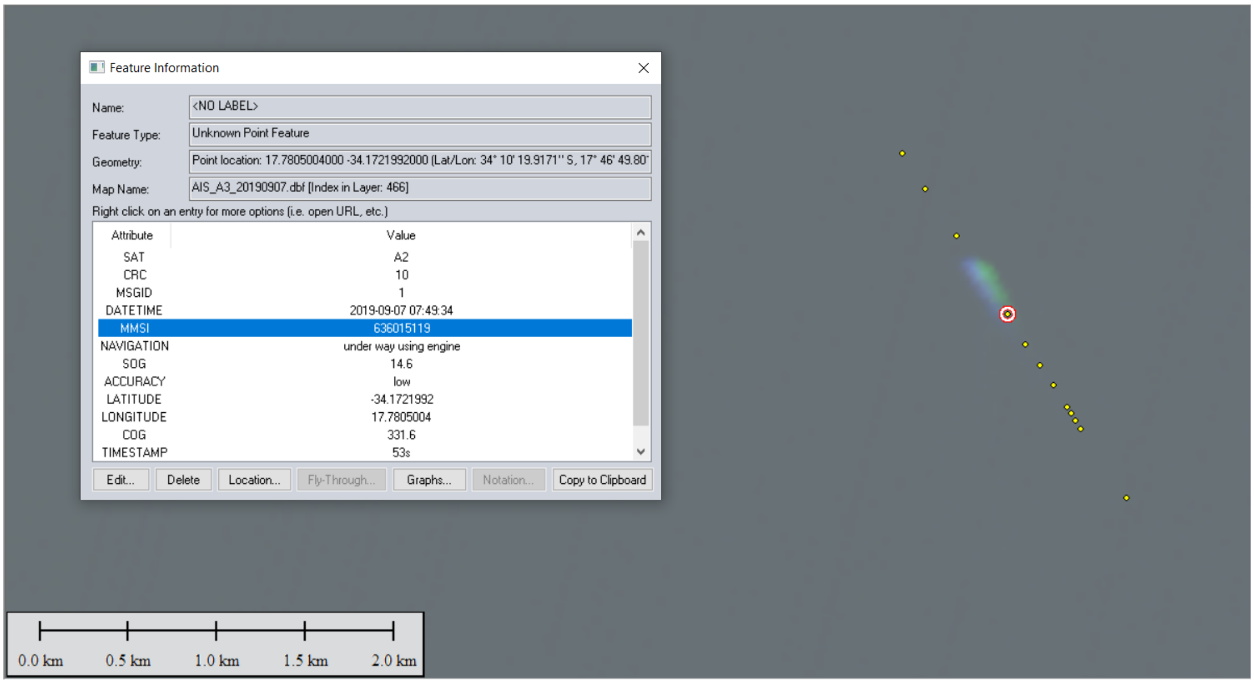

Figure 6.45 AIS and image of tanker ship in Cape Town

Figure 6.46 Picture of the tanker ship. (*ship photo by Cengiz Tokgöz via www.vesselfinder.com*)

Based on the AIS information, the picture of the ship could be seen in Figure 6.46. The size of the ship actually could be measured through the multispectral image. However, a moving ship is more difficult to measure since its back wave is difficult to separate from the ship's real size.

From the Cape Town image and AIS information, 50 ships could be identified through its AIS transmission. However, from those ships, 30 ships could not be matched with its satellite image. Some ships that its image could not be identified are shown in Figure 6.41. Figure 6.47 shows several ships with a low speed or even 0 speed due to its position in the harbor; hence its close proximity with the harbor makes the ships difficult to identify. The difficulty arises due to the medium resolution of the image. Figure 6.44 also shows that at least 3 pixels require identifying a ship in the ocean, which translates to a minimum ship size of 45 x 15 meters.

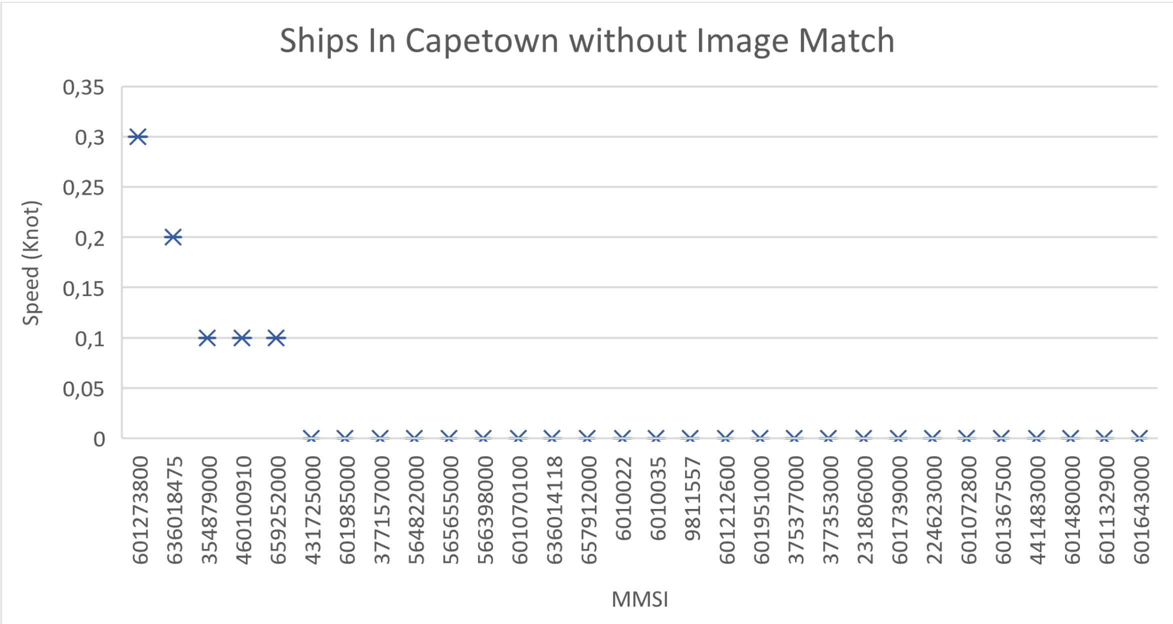

Figure 6.47 Ships without image match.

Another sample of the multispectral image was taken with the LAPAN-A3 satellite performed on 5 August 2018 at 08:25:42-08:26:13 UTC, as in Figure 6.48. Its AIS information is taken from the area that was received between 08:20:46-08:30:46 UTC (10 minutes). The figure shows several ships inside the multispectral image and some ships outside the image area.

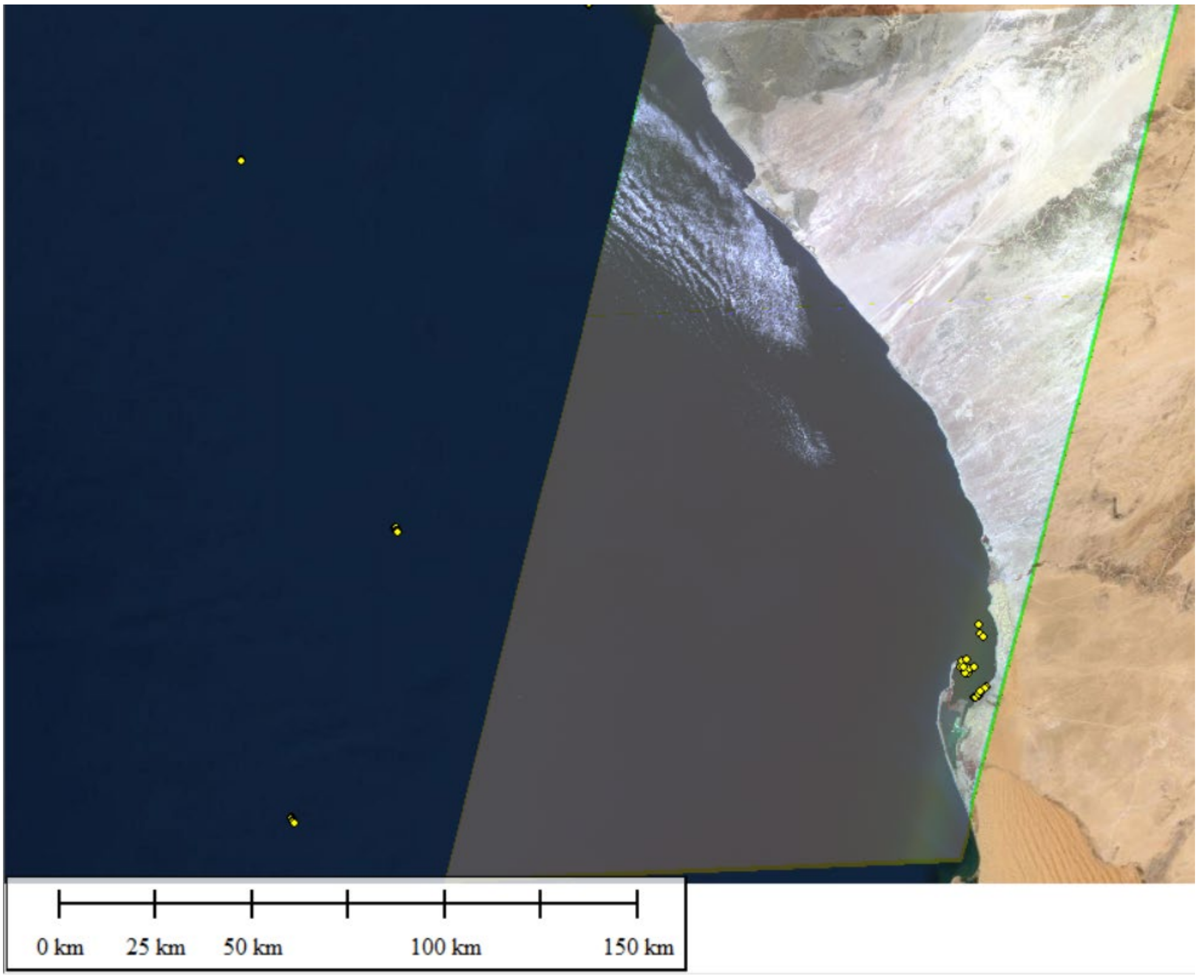

Figure 6.48 Walvis Bay, Namibia image taken by LAPAN-A3 Satellite.

As a previous recommendation, the multispectral image's red channel is used to see the ships around the Walvis-Bay as in Figure 6.49. As seen, there are several ships in the harbor and also in front of the harbor. Even though several AIS of the ships in the harbor could be identified, it is difficult to distinguish ship images.

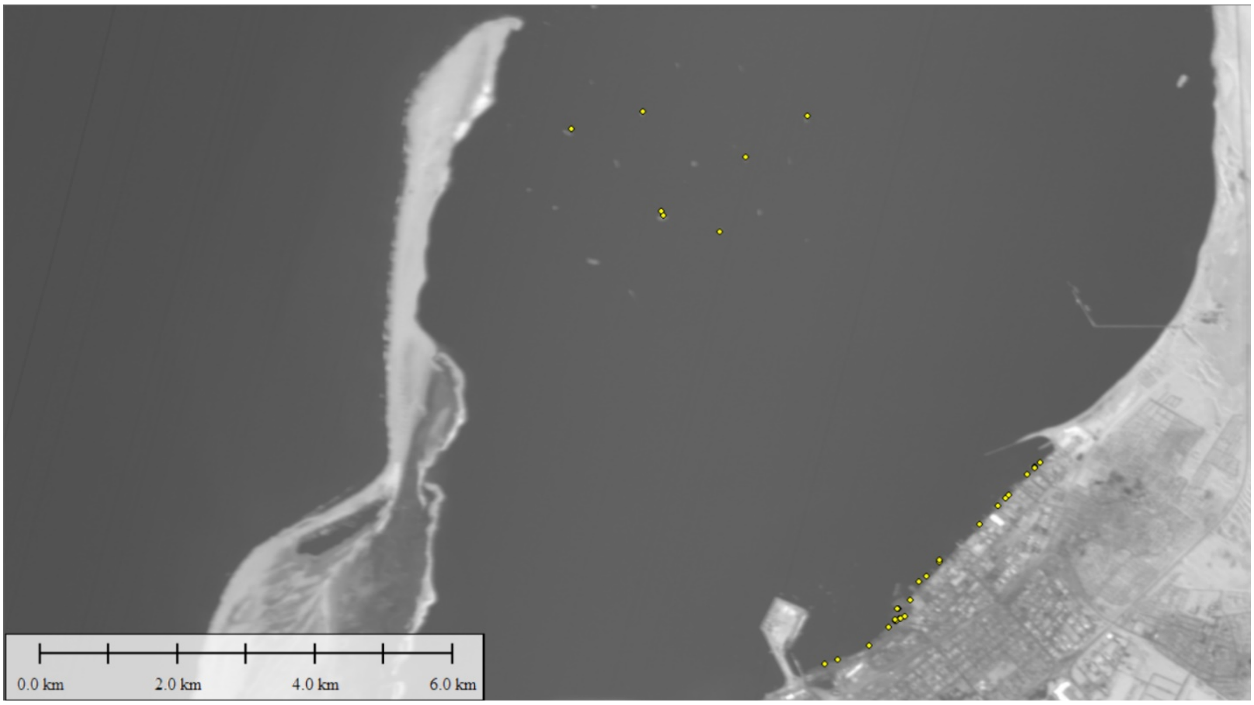

Figure 6.49 Ships in Walvis-bay harbor (Red Spectrum)

In front of the harbor, several ships could be identified by AIS and its image. At least 19 ships image could be identified; however, only eight ships with AIS could be received by satellite. By looking at the AIS data, it could be seen that most of the ships (6 ships) in this area were in anchor or moored position. This explains the low probability reception of AIS data from the satellite. The detection of ships in port or ships that otherwise transmit AIS messages with a 3-minute interval is particularly vulnerable, reducing effective pass duration, especially in dense areas.

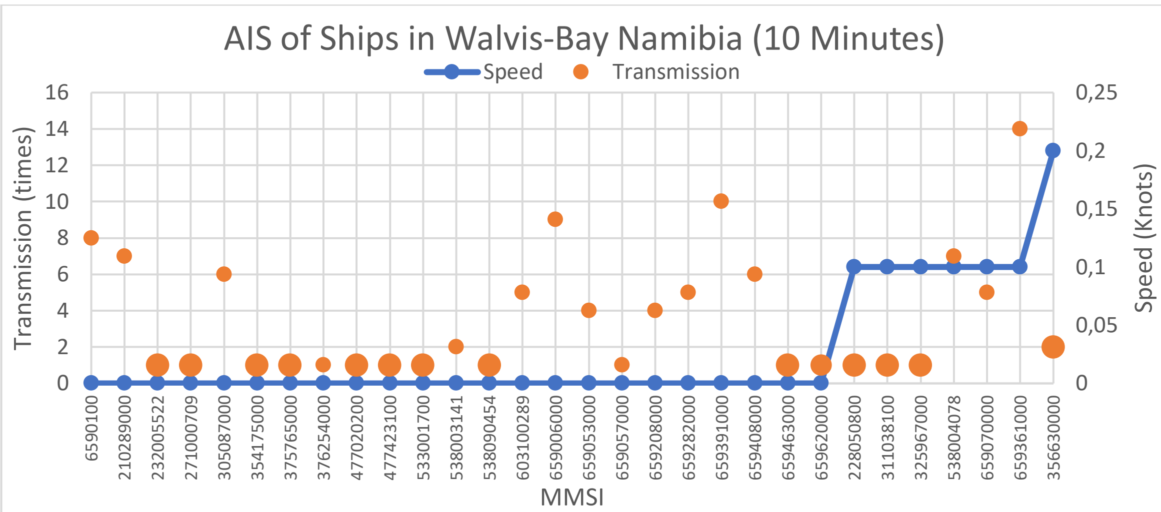

Figure 6.50 AIS of ships in Walvis-Bay received by LAPAN-A3.

Figure 6.50 shows one base station and 29 ships with its speed and frequent transmission in Walvis-Bay received by the LAPAN-A3 satellite within 10 minutes. From the AIS information, it is found that most of the ships at low speed; hence the AIS transmission frequency is reduced, especially for 14 ships in anchor or moored status marked with a bigger dot in the graph.

There is also an interesting ship that is transmitted 14 times. This ship with MMSI 659361000 is a pilot ship that is usually used to guide big ships entering the harbor. By looking at its AIS information, these pilot ships were in maneuver from 317 deg to 314 deg, even though at low speed; hence it transmits its AIS every 10 seconds as required.

7

Summary & Potential for Further Improvement on Future Satellites

7.1 Summary

Automatic Identification System is the radio-based communications system that was initially developed to avoid large vessels from collisions. This device transmits ship information to other vessels and shore stations, i.e., the direction, distance, identification, and location information. At the beginning of the deployment, AIS suffers from a constraint due to the Earth's curvature that limits its horizontal range from shore. Accordingly, AIS traffic information is available only around coastal zones or on a ship-to-ship basis.

The use of satellites to collect and track AIS data from the vessel has dramatically changed the maritime surveillance landscape. The ship's identity is registered and decoded by satellite and then sent for further processing and distribution to ground stations. Improving existing AIS technology already deployed on all large vessels and many smaller vessels around the globe, satellite AIS is revolutionary, providing a comprehensive and global picture of the global maritime shipping environment that can be applied to some cases of safety, security, economic and environmental use. Satellites also enable the detection and monitoring of seafaring vessels around the globe, covering the oceans and the Antarctic.

The vessel monitoring with AIS data needs to be combined with several additional information to get a real ocean situation. As AIS is a cooperative surveillance system, it mostly depends on the vessel. However, the vessel can be easily identified in optical images taken from space without the vessel's need for cooperation. Hence, there is also merit in acknowledging the contribution of ship detection from satellite optical images. There are several systems available that can link to the gathering of information about ship presence and operation. A differentiation between cooperative and non-cooperative systems is typically constructed. With the former, the ships communicate information about themselves. With the latter, observation systems are used to collect information without any cooperation from the ships by fusion of additional information.

While there are some drawbacks to the satellite AIS system due to message collision, several ways to get the solution have been recently done, such as antenna design or antenna placement, advanced AIS receiver processing, and data recovery. This is including new frequency allocation for maritime surveillance through satellite.

Many AIS data providers recently launch satellite AIS in the constellation of nano class satellite to get AIS information from the ships while depending on imaging ships surveillance from other imaging satellite systems. This AIS and image combination with this different type of satellite could be done in the ground. However, since it involves interpolating or extrapolating the AIS positions available before and after the satellite image's acquisition time to get the positions at the acquisition time, the interpolated positions' accuracy is essential for proper data fusion. Due to inaccurate image georeferencing data, minor positional uncertainties may occur between different data sets. However, uncertainties may become substantial due to interpolation if the interval time between received AIS messages is significant and becomes even more difficult in dense ships area.

As shown in the previous sections, the small satellite could serve a surveillance mission by combining satellite AIS and its imaging payload. It also shows that interactive control with a video camera in the LAPAN-TUBSAT satellite enables the finding of good water reflections and traces of ships in the ocean. By combining those two payloads in one satellite, the surveillance of the ship could be done simultaneously. This simultaneous surveillance has the advantage of reducing time constraints for surveillance compares with having separated AIS and imaging payload in a different satellite platform.

For a country in the equatorial region such as Indonesia, the LAPAN-A2 satellite provides frequent revisiting chances. It allows getting continuous data of the ship that could be used to analyze some ship behavior. However, for some areas in the equator, ie. Jakarta harbor, surprisingly polar orbit, has a better reception due to less AIS signal collision at the beginning of the satellite field of view compare with the equatorial satellite since the signal collision happens when its field of view reaches Malaka Strait that has a dense vessel.

The combination of optical images and AIS data simultaneously leads to the following three possibilities:

a. Satellite Image and AIS data match.
   This combination shows AIS information and image information (course, size, and color details for a high-resolution camera). The unmatched result from the ship database and its satellite image could become a sign of illicit behavior.
b. The satellite image exists without AIS data.
   This result may happen due to a weak signal, saturation due to overcrowding vessel, low frequency of transmission due to ship anchoring/mooring, or in some cases, the ship intentionally switches off its AIS transmitter for some illegal activity.
c. AIS data exist without a satellite image.
   This possibility may happen due to the ship being too small to be captured by the satellite imager payload, moored, or docking ship that difficult to be distinguished with the surrounding area or AIS spoofing that happens in several cases.

The assessment of the combination of satellite imagery and AIS shows that for optical observation-only, the maximum resolution possible that usually get small FOV is needed to see the ship details such as size, color, and shape of the ship. However, for comparison with AIS, a maximum field of view is recommended to cover a wide area of the ocean while maintaining the ship's dimension feature for comparison with the database that shows in multispectral from LAPAN-A3 satellite.

Small satellite classes such as LAPAN-A2 and LAPAN-A3 satellites also show that combining both AIS and imaging payload sensors is possible in this class, allowing low-cost development of maritime surveillance from a satellite. Due to the low cost of satellite development, several satellites with payload combinations could be launched and operated for maritime surveillance, mainly supported by the reduction of launch cost in recent years [98].

7.2 Potential for Further Improvement on Future Satellites

It has been studied that maritime surveillance with optical and AIS needs a broader imaging area possible while maintaining the resolution to get more details of the ships such as color, dimensions, and the ships' direction. Even though this quite difficult due to limited imaging sensors with this specification. However, combining several imaging sensors also could be done to solve this problem.

This study proposes that a 5-meter resolution in the LAPAN-A2 satellite is enough to get color and the ships' dimension. However, the wider imaging area, as in LAPAN-A3, also gives an advantage of a broader surveillance area that could be covered. Multiple satellite orbit combination for maritime surveillance also gives an advantage of covering the global ocean area quicker.

The lesson learned from the operation of LAPAN Satellite for maritime surveillance resulted in additional, enhanced recommendations for future satellite development as follows:

- Design improvement of AIS receiver to support simultaneous onboard AIS decoding and digital sampling through enhanced algorithms, multi-antenna support, and superior dynamic range. These enhanced features may increase AIS detection probability from the satellite compare with the existing AIS receiver onboard LAPAN-A2 and LAPAN-A3.
- Using more than one AIS omnidirectional antenna and specific placement in the satellite body. Based on the LAPAN-A2 satellite experiment, 45 degrees of an omnidirectional antenna towards satellite flight direction is optimum to get a better detection rate.
- The minimum 5-meters resolution with broader area coverage is recommended to get more ship features than medium to low resolution.
- More significant data storage allows storing images from maritime surveillance due to a broader area of the ocean.

Besides those recommendations, an additional payload of Visible Infrared Imaging Radiometer Suite (VIIRS) sensor also could be used to detect the ship light, especially fishing vessels during the night [99] [100] and combined with AIS or VMS data. The small SAR satellite combined with AIS may also be another option; however, small SAR spacecraft's design complexity should be considered and depends on payload specifications and how it influences the spacecraft design [105].

For further LAPAN satellite's development, most of those recommendations have been applied in the design of the LAPAN-A4 satellite. The primary mission of LAPAN-A4 is an earth observation using a multispectral imager and support global maritime traffic monitoring using a space-based Automatic Identification System (AIS) receiver, as shown in Figure 7.1. For maritime surveillance, it is better to use four panchromatic cameras looking at different areas. However, since LAPAN-A4 also serve agriculture monitoring, it uses four cameras with a different RGB and NIR spectral band but with a double swath area (~230 Km at 500 Km altitude) compared with the LAPAN-A3 satellite. This satellite also carries a multispectral camera with a 5 & 10-meter resolution and 33 Km swath wider than the LAPAN-A2 satellite. The other missions are scientific research using a space-based magnetometer and experimental thermal infrared sensor [101]. This satellite is currently under development and may be ready to be launched at the end of 2021.

Launch Plan		**~Q4: 2021**
Dimension (mm)		744 x 700 x 520
Mass (kg)		~150 kg
Orbit	**Altitude (km)**	500 km
	Inclination (deg)	97 SSPO
Power		~200 W (EOL)
Communication	**TTC** **AIS** **Payload**	S-Band; 20 kbps/384 kbps Up/down VHF; 156 – 162 MHz X-band, 200 Mbps Downlink

Next Gen AIS & VDES	
Frequency Range	156 MHz – 163 MHz
Sensitivity	< -125 dBm@20% PER
Frequency	87B: 161.975 MHz 88B: 162.025 MHz 75: 156.775 MHz 76: 156.825 MHz 2027: 161.950 MHz (receiving ASM by satellite) 2028: 162.000 MHz (receiving ASM by satellite)
Earth Magnetometer	
Resolution	7 Km/Sample
Bolomoter	Hokkaido University & BPPT

Medium Res Multispectral Camera	
Parameter	*Specification*
Imaging Method	Pushbroom
Multispectral bands	Blue : 450-510 nm Green : 523-605 nm Red : 629-690 nm NIR : 774-900 nm
GSD	16 m@500 km altitude
Swath	230 km@500 km altitude
High Res Multispectral Camera	
Imaging Method	Pushbroom
Multispectral bands	Panchromatic : 410-700 nm Red : 630-700 nm NIR : 770-900 nm
GSD	5 m@500 km altitude
Swath	33 km@500 km altitude

Figure 7.1 LAPAN-A4 Satellite specification.

The AIS receiver of LAPAN-A4 also could receive more maritime frequency, including VDES in new frequency, as discussed in the previous section. This new AIS system allows in orbit frequency change and a possibility to uploads a new algorithm for AIS data decoding.

Besides LAPAN-A4, since the Indonesia area spread in an equatorial orbit, an equatorial satellite is essential, especially for data communication [102]. Moreover, there is a new initiative to develop a constellation of nine small satellites that carry data communication & maritime surveillance such as AIS, IoT, M2M (machine to machine), and also voice repeater payload system in 0-degree inclination as in Figure 7.2. This satellite mostly intended to cover the communication of disaster early warning sensor that spread across Indonesia and also for maritime surveillance [103]. This satellite is called equatorial constellation satellite for communication and now under the design phase and plan to be ready for launch in 2024.

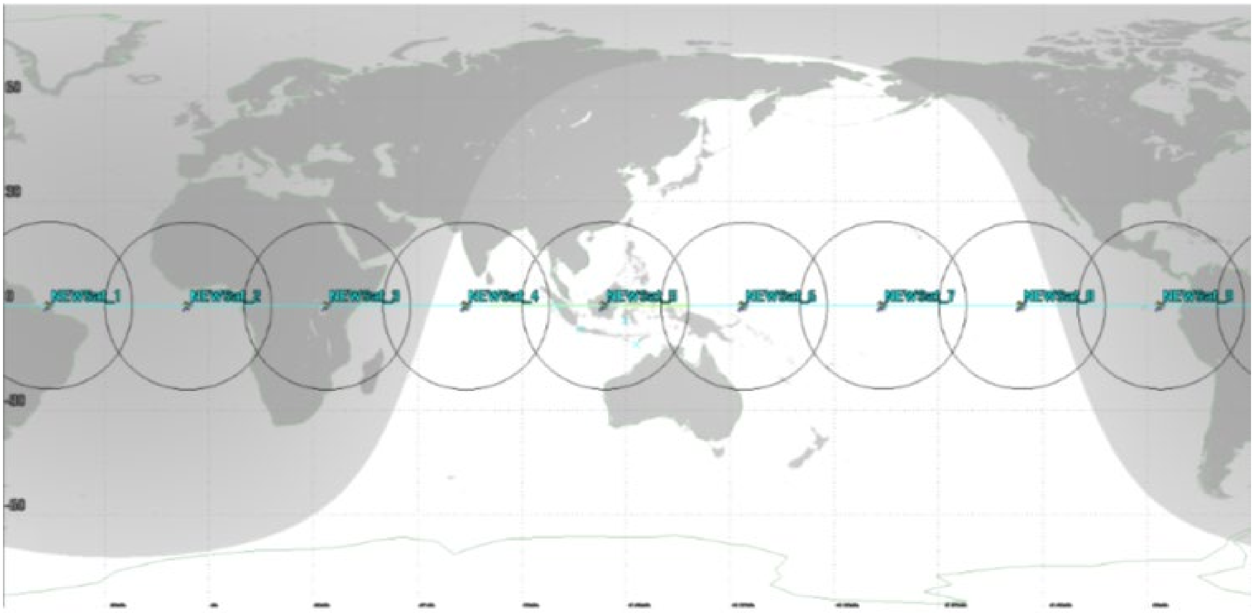

Figure 7.2 Constellation of equatorial communication small satellite.

However, for Indonesia's whole imaging area, two additional satellites are designed in 8 degrees inclination with imaging sensors. With this satellite system, maritime surveillance, especially in the equatorial regions, could be implemented.

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Appendices

A. Estimating Ship Information from Invalid CRC of AIS data Code snippet

The software to estimating the value of ship information from invalid CRC of AIS data snippet shown below. The code developed using Matlab.

```
clc
clear
close all
addpath(genpath('FUNCTIONS')) ;
addpath(genpath('DATA')) ;

load A2_Post_Report_Run.mat ;

max_tgap = 1 ; %in day
MAX_SPEED = 60 ; %in knot
dt = 12 ; %in mins

ShowNormalDataPoint     = 1 ;
ShowRecoveredDataPoint  = 1 ;
ShowDashedLine          = 1 ;
ShowMMSILabel           = 1 ;
ShowTimeLabel           = 1 ;

minZoomToDisplayLabel   = 10 ; %label only shown if lat and lon range
reach this value



data = [CRC MID DT MMSI ROT SOG LON LAT COG HDG];
clear CRC MID DT MMSI ROT SOG LON LAT COG HDG

[TMIN, TMAX] = getTminTmax (data, max_tgap) ;
data((data(:,3)<TMIN) | (data(:,3)>TMAX),:) = [];

BNDATA00 = getTotal(data, 0 );
BNDATA01 = getTotal(data, 1 );
BNDATA10 = getTotal(data, 10);
BNDATA11 = getTotal(data, 11);

dt = dt/(24*60); % mins to days

t = TMIN  : dt : TMAX ;
if (t(end)<TMAX)
    t = [t TMAX];
end

moddata  = zeros(size(data)) ;
oridata  = moddata ;
startmod = 0 ;
for it = 1 : numel(t)-1
    itstart = t(it) ;
    itend   = t(it+1)  ;

    if (it == numel(t)-1)
        tdata = data( ((data(:,3)>=itstart) & (data(:,3)<=itend )) , :
) ;
    else
        tdata = data( ((data(:,3)>=itstart) & (data(:,3)< itend )) , :
) ;
    end
```

B. AIS Satellite with Its CRC Distribution Map Code Snippet

The software developed to create a distribution map of the AIS message from the satellite with its CRC code snippet below. The code developed using Matlab.

```
clc
clear
close all

load AllRun_0105_0705_60s(TimeFilterOnly).mat

CRC = 50 ;
% 1 ALL DISTRIBUTION **************************************
figure(1)

plot(data(:,5),data(:,6),'.') ;
title({['LAPAN-' satname 'Message Position '], ...
        ['Message count = ' num2str(size(data,1)) ', MMSI count = '
num2str(numel(unique(data(:,4))))],...
        [datestr(min(data(:,3))) ' to ' datestr(max(data(:,3)))]})

hold on
plot(Lon,Lat,'k', 'Linewidth',1)
xlim([-180 180])
ylim([-90 90])
xlabel('Longitude')
ylabel('Latitude')

% 2 VALID PLOT ********************************************
figure(2)

oLon    = iout(:,2);
oLat    = iout(:,3);
ZData   = iout(:,6) ;
scatter(oLon',oLat',RC,ZData','filled')
colormap(cmap)

hold on
plot(Lon,Lat,'k', 'Linewidth',1)
xlim([-180 180])
ylim([-90 90])
xlabel('Longitude')
ylabel('Latitude')

title({['LAPAN-' satname ' Valid Message Number '], ...
        ['Message count = ' num2str(size(data,1)) ', MMSI count = '
num2str(numel(unique(data(:,4))))],...
        [datestr(min(data(:,3))) ' to ' datestr(max(data(:,3)))],...
        ['Time step = ' num2str(dt0) ' sec.']})

cb               = colorbar ;
cb.Label.String = 'Message Count' ;

% 3 VALID PLOT (PERCENTAGE) *******************************************
figure(3)

oLon = iout(:,2);
oLat = iout(:,3);
ZData   = sum(iout(:,6),2)   .*100 ./ sum(iout(:,4:7),2) ;
scatter(oLon',oLat',RC,ZData','filled')
colormap(cmap)
```

C. Probability Re-detection of an Already Detected Ship Map Code Snippet

The software developed to create Probability Re-detection of an already detected ship from satellite as code snippet below. The code developed using Matlab.

```
TotalDetect = ZERO ;
sumTCMMSI   = ZERO ; %3D matrices of TC
for i = 1 : numel(MMSI)

    if i ==1
        fdata = data(1: MMSIEndIdx(i), :);
    else
        fdata = data(MMSIEndIdx(i-1)+1: MMSIEndIdx(i), :); % filtering
data based on MMSI
    end
    fdata       = sortrows(fdata,1);  % sort based on timestamp
    iLat        = fdata(:,5);
    iLon        = fdata(:,6);

    TBefore       = -1000 ;
    NDetect     = ZERO ;

    for ii = 1 : size(fdata,1) % track selected MMSI data
        NDetect(iLat(ii), iLon(ii)) = NDetect(iLat(ii), iLon(ii))+ 1;
    end


    TCMMSI = zeros(size(NDetect));
    logic1 = (NDetect > 1);
    TCMMSI(logic1) = NDetect(logic1)./NTotalAcces(logic1);
    sumTCMMSI = sumTCMMSI + TCMMSI ;
   if mod(i,dispcount)==0;
      disp(['Part(2/2) : ' num2str(i) '/' num2str(numel(MMSI))]);
   end


end

PRedetection    = ZERO ;
logic2 = (NMMSI>0) ;
PRedetection(logic2) = sumTCMMSI(logic2)./ NMMSI(logic2) ; % in percent

Pacc = ZERO ;
logic3 = (PRedetection~= 0) ;
Pacc(logic3) = 1 - ((1-PRedetection(logic3)).^(NTotalAcces(logic3)));
Pacc(Pacc<0) = 0 ;
Pacc(Pacc>1) = 1 ;
Pacc = Pacc.*100;

AlphaData = ( (NMMSI>0) );
Pacc(not(AlphaData)) = NaN ;
figure(1)
hnd = imagesc('XData',Lon,'YData',Lat,'CData',nanmedfilt2(Pacc)) ;
set(hnd,'AlphaData',AlphaData) ;
colormap jet
hold on
cline = load('coast.mat');
plot(cline.long,cline.lat,'k', 'LineWidth',1);
xlim([-180 180])
ylim([-90 90])
grid on
```