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MARITIME DOMAIN AWARENESS IN SOUTH AFRICA: A MULTISOURCE APPROACH USING REMOTE SENSING AND AIS DATA

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ABSTRACT:

Maritime Domain Awareness (MDA) is a key factor in ensuring the security, safety, economy, and environment of the maritime domain. Due to the large size of the EEZ, vessel tracking is essential for security, economy, tourism, and safety. However, the failure of one of the two Copernicus Sentinel-1 satellites has posed a significant challenge, hindering the effectiveness of monitoring dark targets. To address this limitation, this study presents the integration of multiple data sources, allowing the mapping of both vessels and dark targets while providing comprehensive analytics to inform decision makers and improve South Africa's maritime domain awareness efforts. The results demonstrated the potential of combining SAR, optical and AIS data to effectively monitor and manage vessel activities in the South African EEZ. Using these diverse data sources, decision makers can gain real-time insights into maritime traffic, identify potential risks or illicit activities, and make informed decisions to protect national interests and promote sustainable practises within the maritime domain.

1. INTRODUCTION

Maritime domain awareness (MDA) is defined by the International Maritime Organisation (IMO) as the effective understanding of anything associated with the maritime domain that could impact security, safety, economy, or the environment. A major component of MDA is understanding and protecting each country's Exclusive Economic Zone (EEZ) (Chintoan-Uta and Silva, 2017, Perera, 2020). The South African Exclusive Economic Zone (EEZ) is one of the largest in the world, covering approximately 1.5 million square kilometres, making it larger than the country's land territory (Walker and Reva, 2020). Being a maritime nation, South Africa relies on the safe, unhindered, and free passage of ships for its economy and security (Potgieter, 2018). The vastness of South Africa's maritime zones underscores the enormous scale of the country's maritime domain awareness (MDA) task.

Vessels weighing more than 300 tons are required to have an Automatic Information System (AIS) on board, which sends data on the location and type of the vessel, according to international regulations (Chen and Wu, 2022). On the other hand, some ships may turn off the devices that transmit position information to the AIS network deliberately or by accident. For example, ships engaged in illegal activities intentionally turn off their AIS transponders and turn them back on when the activities are over (Mazzarella et al., 2017). There are also instances where vessels may choose to provide false information, a practise known as "spoofing" (Chen and Wu, 2022, Tetreault, 2005).

Synthetic Aperture Radar (SAR) enables vessel detection independently of the AIS transponder status by using active remote sensing, making it valuable for maritime surveillance even in areas with poor AIS coverage or when vessels intentionally turn off their transponders. Such vessels are known as "dark targets", where detected vessels cannot be associated with an AIS location. SAR is a remote sensing technology that uses radar mounted on a satellite to create high-resolution images of the Earth's surface. This makes it an integral part of the large ocean area monitoring to improve awareness of the maritime domain where the Automatic Identification System (AIS) transponder is not working, switched off, spoofed, not installed or out of range (Pelich et al., 2019, Rodger and Guida, 2022, Liu et al., 2022, Vicente et al., 2020).

Numerous studies have been presented for MDA using SAR. A large-scale automatic vessel monitoring algorithm based on dual polarisation coherence was proposed in (Pelich et al., 2019). The study demonstrated the effectiveness of their proposed approach in detecting ships, particularly larger vessels, and emphasised the potential of SAR data to supplement AIS data for identifying non-cooperative or "dark" vessels. The authors in (Yasir et al., 2023) reviewed 81 articles published in reputable journals between 2016 and 2022, focusing on the use of deep learning in the detection of ships with SAR imagery. It was observed that after 2018, there was a significant increase in research and publications, underscoring the growing importance of deep learning in this domain. The authors identified the significant role that SAR images play in the ship detection process. These systems combine multiple datasets, including SAR remote sensing data and traditional AIS transponder data, to provide comprehensive and reliable vessel tracking information (Longépé et al., 2018, Vicente et al., 2020).

The Copernicus Sentinel missions consist of free and open satellite data with the aim of monitoring variability in land and ocean conditions (Geudtner et al., 2021). However, the failure of one of the Sentinel-1 satellites has limited the ability of the mission to effectively monitor dark targets (Potin et al., 2022). The use of optical images for ship detection has gained popularity due to the increasing coverage of optical sensors in continuous maritime monitoring (Liu et al., 2022, Hong et al., 2021, Kanjir et al., 2018). A comprehensive review can be found in (Kanjir et al., 2018), where the authors reviewed 119 relevant publica-

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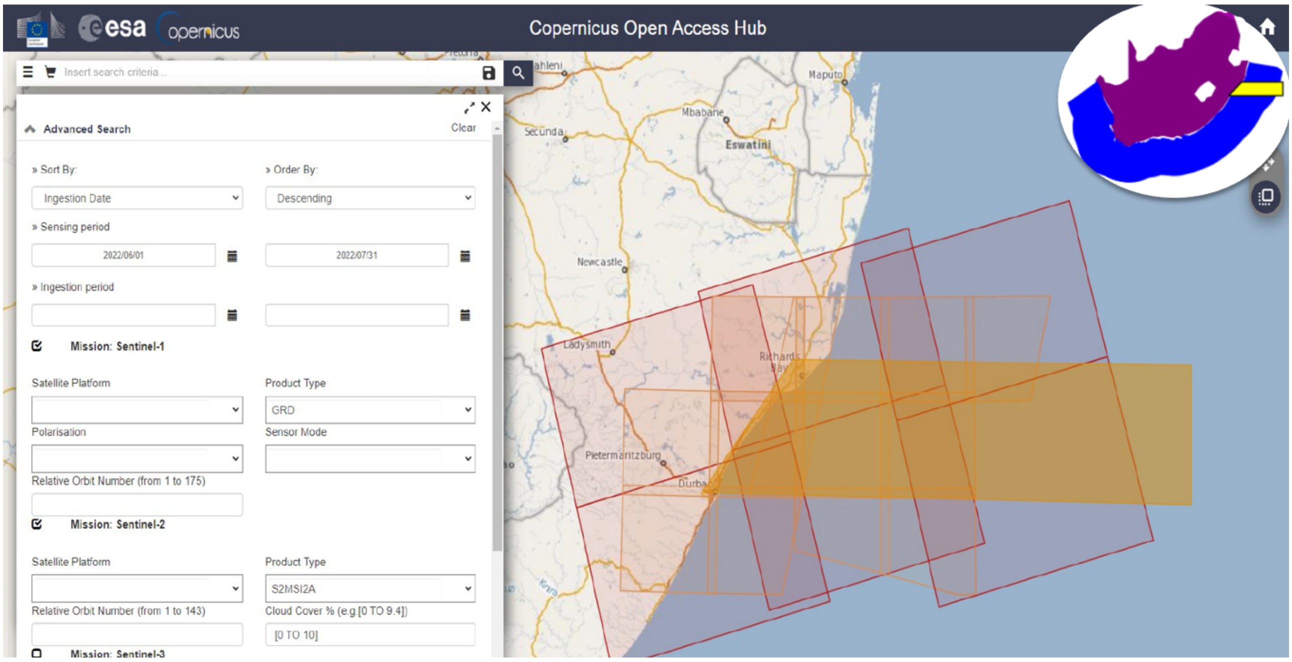

Figure 1: Copernicus Open Access Hub with data search parameters. South Africa Map with study area (top left image).

tions on vessel detection algorithms using spaceborne optical sensors from 1978 to March 2017. The authors predict that remote sensing methods, with the advent of open data, small satellite imaging constellations, and advances in digital technologies, will become fully operational monitoring tools in the maritime domain, improving safety and security at sea.

Although the integration of SAR and optical sensors can improve the reliability of vessel detection, optical vessel detection faces challenges related to complex sea surfaces, including sea waves, wakes, sun-glint, clouds, and small islands (Wang et al., 2018, Kanjir et al., 2018). However, in addition to vessel tracking, multispectral Sentinel-2 satellite data can differentiate marine debris from various coexisting marine features, such as natural organic material, waves, wakes, foam, different types of water (e.g., clear, turbid, sediment-laden, shallow water) and clouds (Hu, 2022, Themistocleous et al., 2020). This capability improves the utility of Sentinel-2 data in a broader range of maritime applications. Furthermore, the Sentinel-2 mission covers coastlines globally, making it well suited for surveillance in coastal and harbour regions. Consequently, numerous studies have focused on combining Sentinel-2 and AIS data for enhanced maritime monitoring (Liu et al., 2022, Kurekin et al., 2019).

The study investigates the integration of multiple data sources (SAR data, Optical data, and Transponder data) for effective monitoring of vessel activity within the South African EEZ. The objective of this paper is to provide information on how AIS, Sentinel-1, and Sentinel-2 can be used to successfully map vessels and dark targets, which in turn provide analytics that will inform decision makers about the behaviour of vessels in the South African EEZ and improve the efforts of the countries MDA efforts).

2. DATASET

This study presents a multisource vessel tracking system that combines satellite Synthetic Aperture Radar (SAR) data, MultiSpectral Optical data, and Automatic Identification System

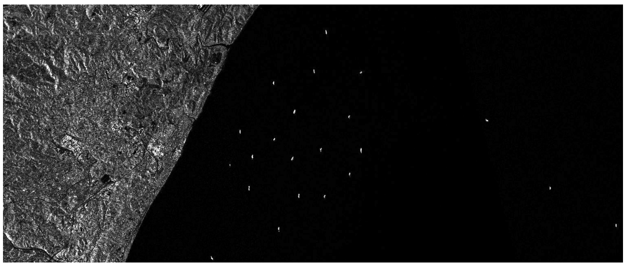

Figure 2: Sentinel-1 IW (VV/VH) image over the study area..

(AIS) transponder data to effectively monitor vessel activity within the South African Exclusive Economic Zone (EEZ). The study area is between Durban and Richards Bay ports in KwaZulu Natal Province, South Africa. The Sentinel family comprises a range of sensors designed for land, ocean, and atmospheric monitoring purposes. The Copernicus Open Access Hub, formerly known as the Sentinels Scientific Data Hub, offers unrestricted and cost-free access to user products from Sentinel-1, Sentinel-2, Sentinel-3, and Sentinel-5P (Tona and Bua, 2018). This study focusses on Sentinel-1 and Sentinel-2 datasets (1). Sentinel-1 is an active radar satellite with a C-band Synthetic Aperture Radar sensor. Sentinel-2, on the other hand, are passive satellites with Multispectral Instrument (MSI) optical sensors.

2.1 Sentinel-1

The European Space Agency (ESA) launched the Sentinel-1 mission, which consists of two polar orbiting satellites equipped with C-band synthetic aperture radar imaging technology. This enables the satellites to operate continuously day and night, capturing images regardless of weather conditions. Sentinel-1A was launched on April 3, 2014, and Sentinel-1B on April 25, 2016. Together, they offer a temporal revisit time of 12 days each, resulting in a combined revisit time of 6 days. However, on 23 December 2021, an anomaly occurred with Copernicus Sentinel-1B, affecting its instrument electronics power supply provided by the satellite platform and causing a disruption in its ability to deliver radar data.

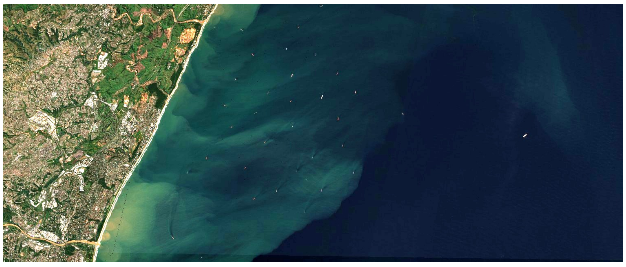

Figure 3: Sentinel-2 Natural Colour composite (Bands 4,3,2) image over the study area.

The data used in the study consisted of Sentinel-1 Ground Range Data (GRD) using two modes:

- Interferometric Wide Swath (IW) with 250 km swath, high (10 x 10 m) and medium (40 x 40 m) spatial resolutions.
- Extra-Wide Swath (EW) with 400 km swath, high (25 x 25 m) and medium (40 x 40 m) spatial resolutions.

Dual-polarisation products are obtained by operating the radar with one (H or V) polarisation on transmit and both simultaneously at receive. Sentinel-1 GRD modes have dual polarisation, that is, co-polarisation (VV or HH) and cross-polarisation (VH or HV), see Figure (2).

2.2 Sentinel-2

The Copernicus Sentinel-2 mission encompasses a constellation of satellites equipped with multispectral imaging (MSI) instruments, providing wide-swath imagery with high temporal and spatial resolution. The Sentinel-2 optical sensor captures images with a ground sampling distance (GSD) ranging from 10 m to 60 m, with a five-day systematic five-day revisit time. The twin satellites, Sentinel-2A and Sentinel-2B, were launched in 2015 and 2017, respectively.

Table 1: Sentinel-2 MultiSpectral Instrument (MSI) Bands.

Band	Central wavelength (nm)	Resolution (m)	Descriptor
1	442.7	60	Aerosol
2	492.4	10	Blue
3	559.8	10	Green
4	664.6	10	Red
5	704.1	20	Red Edge 1
6	740.5	20	Red Edge 2
7	782.8	20	Red Edge 3
8	832.8	10	NIR
8°	864.7	20	Narrow NIR
9	945.1	60	Water vapour
10	1373.5	60	SWIR Cirrus
11	1613.7	20	SWIR1
12	2202.4	20	SWIR2

Similarly to the Sentinel-1 mission, the Sentinel-2 mission comprises a constellation of two twin satellites, namely Sentinel-2A and Sentinel-2B. Sentinel-2 data offer more precise details in the spatial and spectral domains compared to SAR data and are not affected by intrinsic noise, see Figure (3). Sentinel-2 is equipped with the Multi-Spectral Instrument (MSI), which acquires 12 bands in the visible, near-infrared (NIR), and short-wave infrared (SWIR) spectral windows, listed in Table (1).

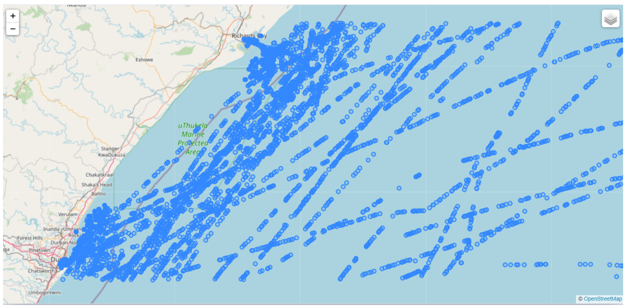

Figure 4: AIS vessel positions within the study area (date: 01/06/2022).

2.3 AIS Data

The study involved the use of AIS, an Automatic Identification System on ships, which relies on transceivers to generate static real-time information (e.g., name and type of the vessel) and dynamic information (e.g., position and speed), see study area coverage for one-day in Figure (4). Data sources included historic AIS data and Sentinel-1 and Sentinel-2 data acquisitions within the designated study area. The AIS data within the study area were systematically decoded and stored in the database for subsequent analysis and application. Integrating AIS data with Sentinel-1 and Sentinel-2 satellite data enables a comprehensive understanding of vessel activities and movements within the region of interest.

3. METHODOLOGY

The study proposed a multisource vessel tracking system that combines satellite Synthetic Aperture Radar (SAR) data, MultiSpectral Optical data, and Automatic Identification System (AIS) transponder data to effectively monitor vessel activity within the South African Exclusive Economic Zone (EEZ). Figure (5) shows the system architecture of the multisource approach using SAR and optical ship detections and the AIS transponder data is presented in Figure (5).

For the purpose of this study, multiple Sentinel-1 and Sentinel-2 datasets were obtained from Copernicus Sentinel Open Access Hub[1]. The study area was covered by nine and twelve Sentinel-1 and sentinel-2 tiles, respectively. Overall, eight tiles with 82 optical scenes covered the ocean area of the study with a 10% maximum cloud cover. 29 SAR scenes were found within the study area. The data search was from the beginning of June to the end of July 2022 (Winter Season).

Sentinel-1 images were preprocessed using the SNAP toolbox, see Figure (6). The data was first split into sub-swaths to focus on the study locations and reduce the size of the image to improve processing efficiency. The orbit state vectors provided in the metadata of an SAR product are generally not accurate and can be refined with the precise orbit files. The orbit file operator in the SNAP toolbox automatically downloads the latest released orbit file and applies it to the image so that the image can be geocoded more precisely.

For the Sentinel-2 data, multiple pre-processing steps are applied, including; an atmospheric correction, topographic correction, resampling, band stacking, and image sub-setting . Sentinel-2 Level-2A bottom-of-atmosphere (BOA) products that we acquired are already atmospherically corrected.

[1] https://scihub.copernicus.eu/

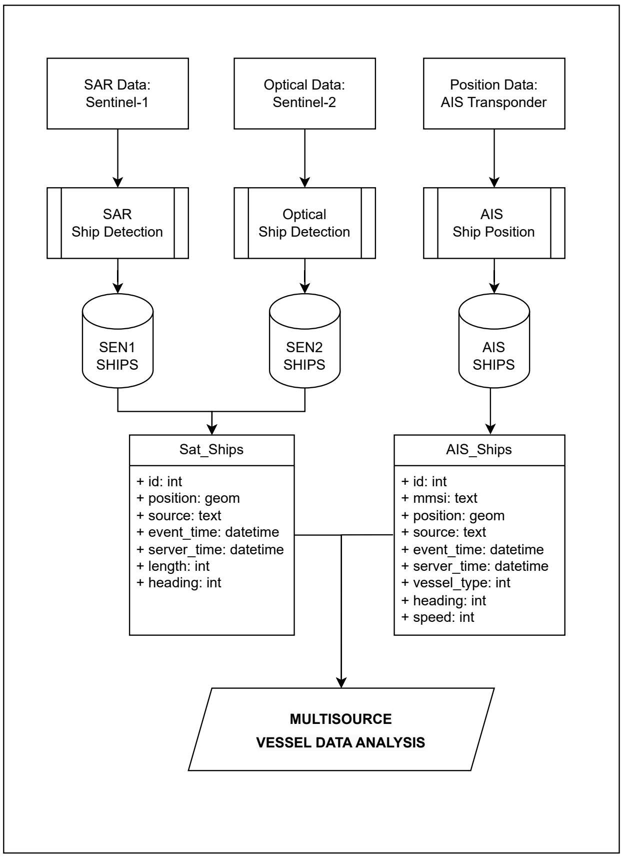

Figure 5: A multisource approach using SAR data and optical data ship detections and AIS transponder data.

3.1 Sentinel-1 Ship Detection

On the SAR image, ships generally appear as bright spots associated with high backscattering values, whereas the surrounding smooth sea surfaces appear as dark areas characterised by low backscattering values. Following preprocessing, the image is ready to be used in the ship detection procedure. The ocean object detection operator of the SNAP tool recognises objects such as ships on the sea surface using SAR images. Object detection operations are divided into three steps: land-sea masking, prescreening, and object discrimination. Land–Sea Masking is used to mask the land area that minimises the erroneous detection of light poles, bridges, and land mass, which appear as bright pixels in SAR images. By default, the SRTM 3-sec digital elevation model is used to detect and filter off regions of positive elevation. Adaptive thresholding was used for the prescreening process. It applies moving windows, and depending on each pixel under test, a new threshold is calculated based on the statistical characteristics of its local background. If the pixel under evaluation is higher than the threshold, it is considered an acceptable target. SNAP's CFAR algorithm for ocean object detection assists in the quick detection of ships.

3.2 Sentinel-2 Ship Detection

For ship detection using Sentinel-2 datasets, a visual examination was performed on the normalised difference water index (NDWI). The presence and quantity of water in an image are quantified using the NDWI product. It is used in satellite imagery to emphasise open-water features, allowing a body of water to stand out against soil and vegetation. The NDWI is calculated using band 8 (NIR) and band 12 (MIR) of Sentinel-2 data,

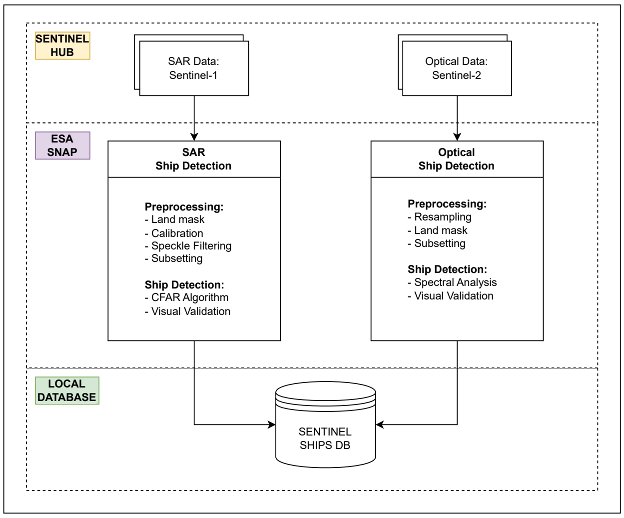

Figure 6: SAR and Optical Vessel Detection Methods.

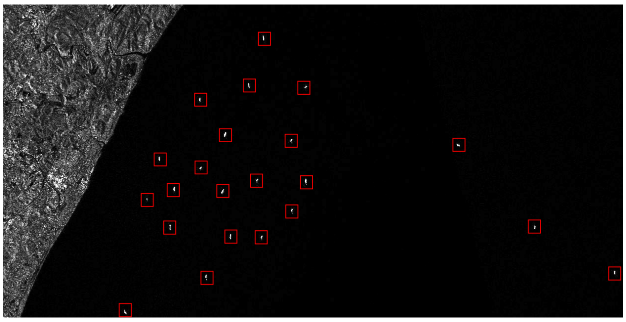

Figure 7: Sentinel-1 Vessel Detection (Marked in Red).

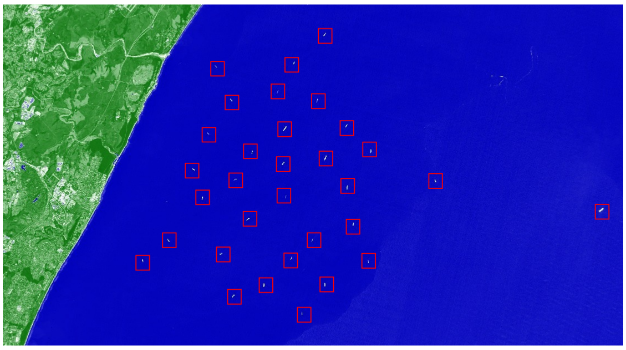

Figure 8: Sentinel-2 Vessel Detection (Marked in Red).

allowing it to detect small changes in the water content. When ships are present in an ocean landscape, their reflectance pattern differs from that of water. Because of their structural materials and colours, ships often reflect less near-infrared and more visible light. This contrast in the reflectance values between ships and water can be captured by NDWI, making ships appear as a white patch that can be identified using visual inspection. Ship locations are extracted and saved to a database.

3.3 Multisource Analysis

Based on the results of ship detection, the SAR, Optical and AIS ships databases analysis can be carried out. First, linear interpolation (or extrapolation) is used to estimate the approximate position of the AIS data at the acquisition time of the satellite images. This is because AIS transmission occurs continuously, while remote sensing images are collected at fixed time intervals. Then an association relationship is constructed based on

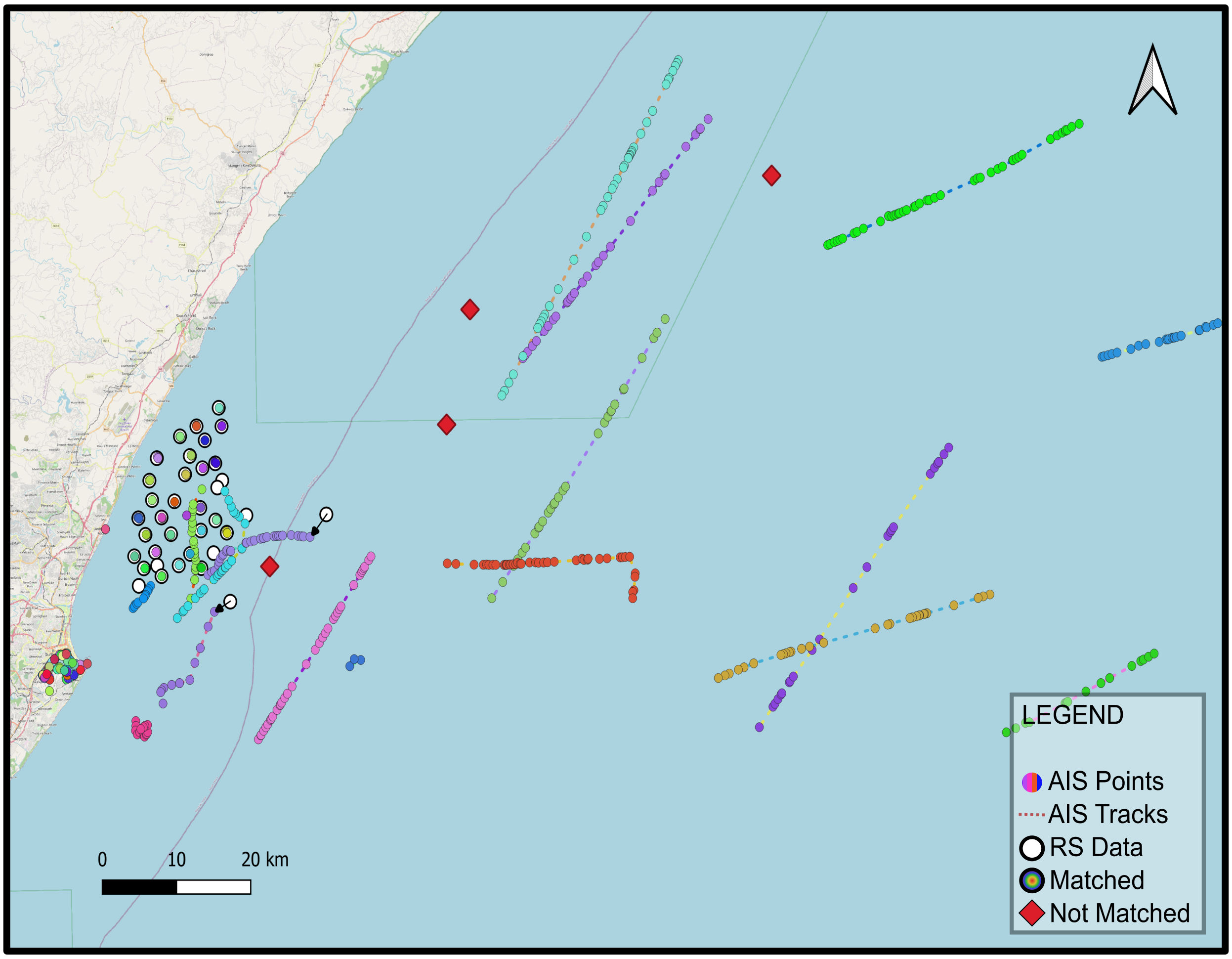

Figure 9: Multisource vessels analysis map (AIS and Remote Sensing Data).

the features of satellite detected ships and the estimated AIS data. By defining a "buffer" around the *RS detected ship* and the *AIS historic/interpolated vessel tracks* we can identify the intersected and nonintersected ships, by analysing the information from the two data streams.

4. RESULTS AND DISCUSSION

The study proposed a multisource approach to monitor vessel activity within the South African EEZ. To achieve this objective, a combination of remote sensing (SAR and optical data) ship detections and AIS transponder data were analysed. SAR data allowed the detection of vessels even during low light or adverse weather conditions. Figure (7) shows detected ships (in red squares) from a SAR image. Optical data provided high-resolution imagery that was used for vessel identification of smaller vessels and can also be used for classification of vessel types. Figure (8) shows detected vessels (in red squares) using spectral signatures from an optical image.

Table 2: Multisource analysis: A comparison of Optical (Sentinel-2), SAR (Sentinel-1) and Transponder (AIS) data.

Feature	SAR: Sentinel-1	Optical: Sentinel-2	Transponder: AIS
Ocean Spatial Coverage	High	Low	Very High
Image Spatial Resolution	Low	High	Very High
Temporal Resolution	Low	Moderate	Very High
Weather Conditions Effects	Low	High	Very Low
User Dependency	Low	Low	Very High
Data Costs	Very Low	Very Low	High
Vessel Identification	Low	Moderate	Very High

It is evident that remote sensing is a viable option for ship surveillance (e.g. when AIS transponders are switched off). Table (2) shows an analysis of the limitations of the different data sources used. The analysis showed while remote sensing can be used as a standalone system to detect ships, it cannot provide relevant identity information (such as vessel name, speed, and heading). Also, remote sensing data may not always be accessible due to satellite revisit restrictions, atmospheric opacity, or other obstructions. However, when a combination of remote sensing and AIS is used, the sensors were able to overcome their respective limitations, as demonstrated in Table (2). Optical data offered high spatial resolution that allowed identification of smaller vessels but is limited by clouds, weather, and daylight conditions. SAR data overcame this limitation by providing all-weather monitoring, penetrating through cloud and darkness, but lack visual details and have lower resolution. Sentinel-1 SAR temporal resolution is also not ideal with 12 day rivisit time. AIS data offers real-time vessel tracking and useful information but depends on vessels having AIS transponders, and vessels not temparing with the equipment.

The combination of remote sensing and AIS data can associate moving ships in different systems, providing support for remote sensing target recognition and tracking of moving ships. Furthermore, the integration of multisource monitoring can enhance the monitoring of non-compliant and illegal ships so that appropriate search, rescue, and enforcement measures can be taken, as shown in Figure (9). By merging and processing these datasets, a comprehensive understanding of vessel activity within the South African EEZ can be achieved.

5. CONCLUSION

The number of vessels travelling in the marine environment has increased, leading to a greater focus on maritime surveillance. This study proposes a comprehensive vessel tracking system that combines Synthetic Aperture Radar (SAR), optical, and Automatic Identification System (AIS) data to provide analytics that will help decision makers better understand the activity of vessels in the South African Exclusive Economic Zone (EEZ). The results of the study demonstrated the potential of using multiple datasets for effective vessel tracking and monitoring, which can contribute to improved maritime security, increased economic activity, and environmental protection. Further work includes up-scaling and automation of the proposed system.

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