Maritime Radar: A Review on Techniques for Small Vessels Detection

Suraya Zainuddin, Idnin Pasya, Nur Emileen Abd. Rashid, Nadiy Zaiaami, Asiah Maryam, Raja Syamsul Azmir Raja Abdullah and Megat Syahirul Amin Megat Ali

***Abstract*— Maritime radar is an essential technology for observation and tracking systems in various marine applications. In comparison with terrestrial radar systems, maritime radar faces the challenge of large clutter signals, contributed by sea waves. This problem becomes more critical when the system is detecting relatively small vessels, where the probability of detection is reduced due to small radar cross section (RCS) of the vessels themselves. This paper presents a review of recent techniques in maritime radar, developed to overcome this issue, discussing several aspects such as (i) system topology, (ii) radar waveforms, and (iii) detection algorithms. Considering the recent works in this area, several recommendations for future works are presented to further improve the performance of modern maritime radar detecting small vessels.**

***Index Terms*— review; maritime; marine; radar**

I. Introduction

RADIO Detection and Ranging (RADAR) has been developed from the early 19th century, for the purpose of detecting and tracking a specific target at a required distance. Its core fundamental evolves around short burst of electromagnetic signal transmitted from a transmitting antenna, reflected by a target and returned as an echo signal into the receiving antenna. The returned signal do not only provides information of the target's presence and position, but also supplies other information that can be exploited to estimate the target radial velocity, angular direction, size and shape of a target [1]. Furthermore, depending on the signal processing technique, the radar may have additional functionality, for instance, the ability to track target's movement, and predict its trajectory. Due to these abilities, radar sensor has been an essential technology in surveillance and reconnaissance tasks; throughout all-weathers and all-day operations, either for terrestrial or maritime environment [2].

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In recent years, there is a growing interest for radar application in maritime environment, where radars are being utilize for security and defense purposes. As for maritime, applications of radar is being implemented in several modes in order to support maritime operations [2], such as:

(i) ISAR imaging of ships
(ii) Maritime target tracking
(iii) Maritime moving target indicator (MMTI)
(iv) Open-sea long-range surveillance and vessel detection
(v) Range profiling of ships
(vi) Small maritime target detection

Maritime traffic monitoring is more paramount when involves congested areas which were investigated by many scholars such as improvement of the Radar Network of Cooperative Vessels (RNCV) system coverage maps [3] and utilization homogeneous moving sensors in a dense area [4]. From literatures, it was notable the marine radar implementation has been acknowledged in day-to-day applications; For example, to analyze the observed wave and current fields for coastal water characterization [5] and for the usage of real-time oil spill monitoring [6].

While marine radar is developing rapidly, small vessels detection has becoming the area of interest for prevention of illegal activities such as piracy, smuggling, terrorist attack, human-trafficking and illegal intrusion of country's maritime boundary [7][8]. In addition, it is also crucial for collision avoidance due to vulnerable target detection. Various aspects had been explored by scholars with regards to this scope of area, traversed from a shore-based [7] to space-based [9] system and extension of radar system to a vessel-mounted based [10]. Even though many approaches and works had been done in several angles such as system topology, design, and detection algorithm, nevertheless there are still continuous explorations for a better small vessel detection radar system performance.

In this paper, we reviewed various recent techniques explored by multiple scholars in maritime radar through several angles such as radar topologies, waveforms and algorithms for signal processing. Subsequently, by contemplating recent researches in this area, several recommendations are discussed for future improvement in small vessels detection.

The remaining parts of the paper comprises a review on the evolution of recent maritime radar systems in section 2. Section 3, maritime radar systems topology and detection techniques are discussed which leads to section 4 on the recent techniques for a small vessel detection. Finally, section 5 concluded the paper together with possible future works which provide a promising method to overcome the challenges.

II. Evolution of Maritime Radar Systems

The history of radar technical advance was started during Second World War (WWII) exploring its capability as a defensive weapon and the technological development efforts post-WWII were then undertook by countries to build their own radar equipment [11]. Maritime radars were in placed mainly for maritime navigation and have evolved from the early years of radar, going from analogue to digital systems, and recent trend from static systems to portable radar systems.

Radar begins with a static system, which it is still being utilize majorly in maritime surveillance until to date despite of some of it well-known drawbacks. A system such as ISRA (Indonesia Sea Radar) FMCW S-band coastal shore-based radar, doesn't offer flexibility of radar's coverage area due to it was installed fix on shore. Its range of detection was relative to parameters such as height of antenna against the sea water level, height and size of target, transmitted power, receiver's sensitivity, receiver's dynamic range and weather conditions [12]. Due to static implementation [12], target can only detected at limited range (in this case is up to 10.8 km) as it was hard to maintain the calibrator mounted on target to always face the radar site due to the effect of sea waves. In addition, other hindrances within the radar coverage area may also obstruct radar from detecting targets [12]. However, there are many ventures to overcome the issues of fixed system, one of it is through introducing portable radar platforms.

On the other hand, in portable applications, radar normally installed or mounted on moving elements; such as to aircraft [2] and vessel [3][10][13] or buoy [14]. It boosts existing radar features by offering more flexible coverage area due to radar is movable. Apart of various attempts of portable platform, there were also efforts over Synthetic Aperture Radar (SAR) for improvement of maritime reconnaissance and monitoring. SAR has been exist years back, but it started to take place in maritime surveillance for the past few years [15][16]. [17] reviewed the potential space-borne SAR to be exploited for maritime activities monitoring. While, there was also a comparative study done on satellite-borne SAR as an operational vessel detector for surveillance [15]. SAR is acknowledged for its high resolution properties, independent of sunlight, resistance to adverse atmospheric conditions and sensor's large swath widths [18]. Thus, it provides better insight of current maritime environment and condition. However, there are still some hitches in this quite newly explored technology which are; inability to determine the target's azimuth, incapability to deliver actual data about the target's shape in most conditions and incompetence to identify vessel that is smaller than 15 m; in which reduces the detection probability of small vessel while increases error due to false detection more over if there are disturbances [19].

A joint technology is also being considered to improve existing radar's deficiency. Recently, Automatic Identification System (AIS) data also has been incorporated with maritime radar to enhance detection [3][20]. There was also a discussion on AIS approach and how it can be extended to a real-time (RT) AIS via application-service messaging (ASM), for a cost-effective global ocean observing and monitoring [20]. A study on joint implementation simulation between radar system and AIS data also had been done for detection of a vessel presence and absence [18]. Proud et al. (2016), evaluated AIS as an existing technology with prospective over maritime tracking and observation due to there was (i) a range limitation of off shore-based technologies, (ii) existing space-based radar and other sensors' technologies have coverage limitation, and (iii) deployment of a marine patrol and synthetic aperture radar (SAR) asset if to cover a wide area are costly [17]. Collaboration between existing radar system and AIS shall contribute to a better prospective in future maritime monitoring.

Other latest advancement in maritime radar technology was a fully coherent dual band (S- band and X-band) radar system with a single photonic-assisted transceiver that utilizing the benefit of multiband and it was a cost-efficient approach [21]. It resulted detection of multiple targets at difference distances and likely equal to the AIS navigation data [21]. Fig. 1 illustrates the developed system and test site of a dual band radar system based on a single photonic-assisted transceiver [21]. In year 2015, the first photonic-based radar system demonstrator in a real maritime environment had been experimented and compared against a commercial system of maritime applications by 'GEM Elettronica' and resulted that the proposed approach may lead to new advances in radar architecture, by the development of a total frequency and waveform agility, an application-transparent photonic transceiver [22].

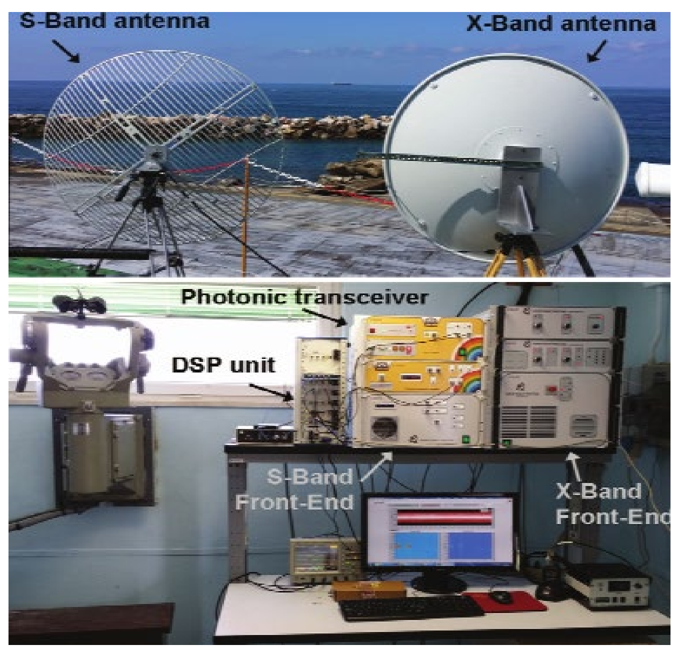

Fig. 1.The developed system and test site of a dual band radar system based on a single photonic-assisted transceiver [21]

In addition of previous mentioned radar technologies, Noise Radar Technology (NRT) was also been explored. NRT has advantages over more conventional radars which utilize deterministic waveforms. Besides, it enhances radar technical performance through low Probability of Interception (LPI). Galati et al. probed into the prospect of Noise Radar Technology (NRT) implementation for mitigation of the mutual interference between marine radars that operating in the similar band in a marine dense area, which degraded radar system's Probability of Detection [23]. In the study, Low Probability of Interception/ Exploitation of radar signals is the key interest through the design of non-deterministic waveforms [23]. The research exposed the potential NRT for future operational radar inclusive marine navigation [23].

The evolution of maritime radar is not only limited to radar system design and algorithm. Marine radar simulator is important for radar training as radar utilization for collision avoidance is irreplaceable. Simulator is widely used for training due to it is economic, changeable and reusable [24]. Due to radar's vital role as the main navigation equipment in marine, radar simulator development is crucial. However, modern radar simulator turns to have defect such as the outmoded single function operation interface and there was a large gap between simulator and radar [24]. Thus, [24] had proposed a new method to design and develop a novel radar simulator based on WPF (Window Presentation Foundation) framework which complied IMO (International Maritime Organization) general radar simulator performance with add-on features which benefit for radar training. Simulation resulted an attractive interface, reasonable layout and easy handling [24].

By reviewing some of the current research trend in maritime radar, it exhibits the continuous growth in various radar segments and indicates a non-stop exploration pitch in for a better maritime radar system.

III. Maritime Radar System Topology and Detection Techniques

A lot of effort had been done towards the growth of maritime radar. Key parameters for design involves (i) radar system topology, (ii) selection of suitable signal, (iii) detection mechanism, (iv) signal processing algorithm and (v) radar imaging. Thus, scope of research in maritime radar evolved within these areas of study. There were also works done for benchmarking and improving on the existing system.

A. Modern Maritime Radar System Topology

In this section, we discuss the common radar system topologies which related to placement of radar's transmitter(s) and receiver(s). It can be categorized into three types of arrangement which are:

(i) Monostatic
(ii) Bistatic
(iii) Multistatic

Fig. 2 illustrates the basic topology of radar systems consist of monostatic, bistatic and multistatic.

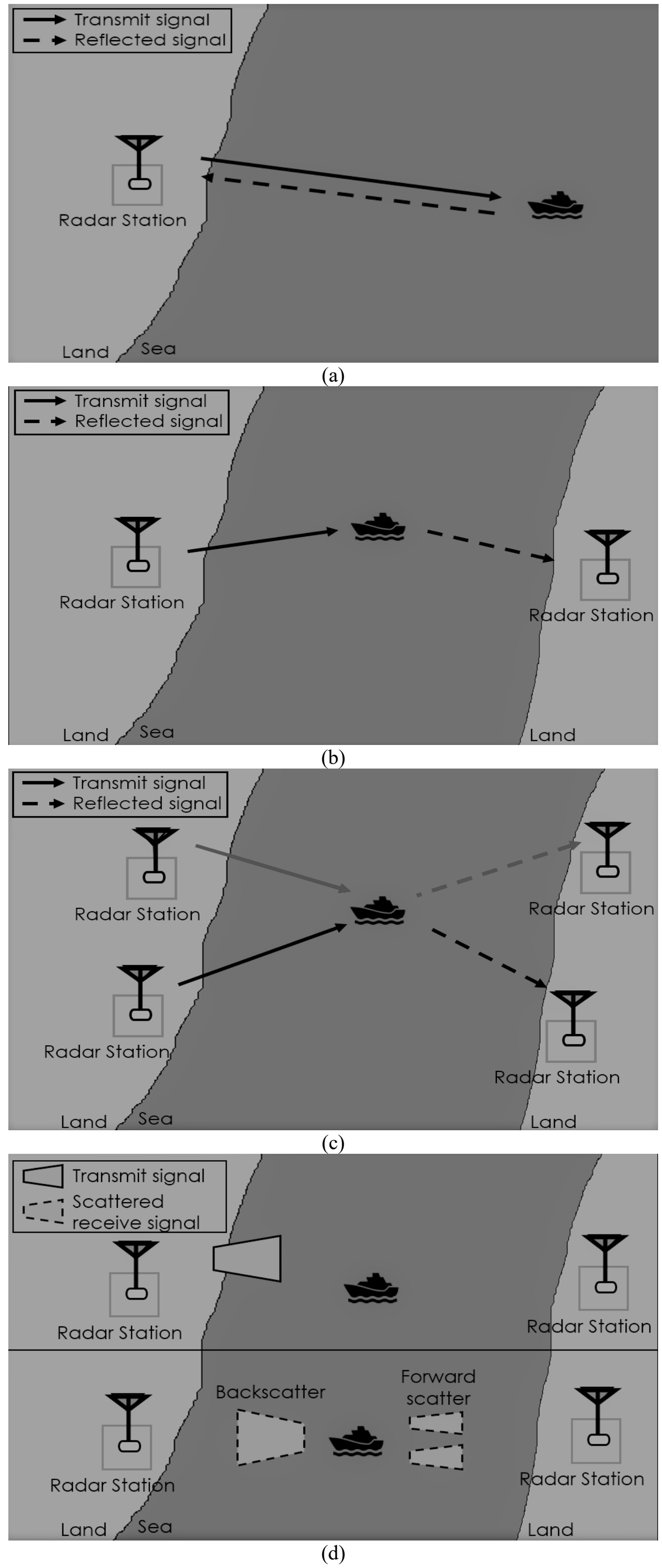

Fig. 2.Illustrations of basic radar topology (a) monostatic, (b) bistatic, (c) multistatic, and (d) backscatter radar (BSR) and forward scatter radar (FSR) concept.

1) Monostatic and Bistatic – as Based of Topology

Monostatic refers to a single-site configuration where transmitter and receiver of a radar are collocated at the same location; Basically only an antenna used at both sides [1][25]. Most of existing conventional maritime radar systems for vessels detection are deploying monostatic topology, as they utilized a shore-based high-power radar. ISRA S-Band coastal surveillance radar utilized in [12] was an example of a monostatic topology. For a monostatic detection, target location can be dictated by a time delay measurement and an antenna bearing, by knowing the length and orientation of the baseline [26].

Contrary, bistatic radar as it was termed by K. M. Siegel and R. E. Machol in 1952; detach its transmitter and receiver to two separate sites with a considerable distance [1]. Main value of a bistatic radar which always been exploited is its wider spatial coverage apart of refining the isolation between transmitter and receiver [27]. Furthermore, bistatic determines target location through the time of propagation from a transmitter to a target to a receiver which defines a prolate spheroid with transmitter and receiver sites as foci [26]. Where then, the location of a target on the spheroid surface is calculated by the azimuth and elevation angles of the transmitter antenna [26]. Kabakchiev et al., did an experimental verification of low profile (small and slow) maritime target detection by utilizing forward scatter radar (FSR), a special type of bistatic radar that serves in a narrow scattering area along the transmitter-receiver baseline [28]. In this case, the FSR cross section may increase by order of magnitude compared to monostatic RCS [28]. Fig. 2 (d) depicts the conceptual idea of FSR and also backscatter radar (BSR) system. Further explanation on both systems are discussed at section III (b).

2) Monostatic and Bistatic – as Based of Topology

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3) MultistaticTopology

Multistatic radar is the variation developed from bistatic radar. Basically at the earlier stage, multistatic radar utilizes two or more separated receiving antennas operating with a single transmitting antenna [27]. This type of topology had been adopted by [7], in their work comparing a multistatic and forward scatter radar for a small maritime target detection. Fig. 3 depicts the experimental setup comprised a multistatic and forward scatter radar [7]. For this experiment, multistatic topology was a combination of a monostatic transceiver node with two multistatic receive-only nodes (Blue colour nodes) [7].

Besides, multistatic topology also can be a blend of multiple pairs of transmit and receive antennas. It is possible to be formed using multiple monostatic or bistatic radars, and a mixture of the two are also possible [25][29]. In a multistatic antenna geometry; multiple transmitters can also be implemented, where, they are coherently phased at each site and deliver as a single transmitting array which is known as distributed array radar [27]. This introduce to a further system geometry which is known as MIMO.

A multistatic radar system mainly was favored due to its ability to [29]:

- Increase accuracy as a result of collaboration between a bistatic and a monostatic geometry increase the number of vector solutions for the total vector combination.
- Reduce the geometric error of total surface current measurement.
- Increase the resiliency as the system capable to provide additional coverage.

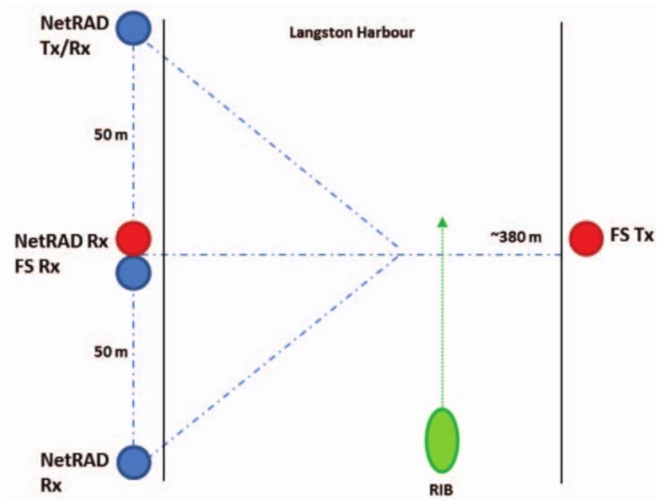


Fig. 3.Sketch of experimental setup with multistatic deployment (Blue nodes) [7]

4) *Evolution to MIMO Geometry*

The latest that draw interest in radar research, is familiarly known as multiple-input multiple-output (MIMO) radar which is a diversification from a multistatic topology – which involves utilization of multiple antennas at its transmitter and receiver sites. MIMO radar is able to transmit multiple signals that are orthogonal, correlated, or partially correlated to each other; and by a proper signal selection, it will increase the degree of freedom over a conventional phased array radar with similar number of antennas; in terms of improvement on the resolution, number of detectable targets and its robustness against radar cross section (RCS) fluctuation [25][30].

In MIMO topology, one needs to deal with multiple antennas configuration and the commonly addressed group in literature, namely: (i) collocated MIMO radar and (ii) statistical MIMO radar [31]. A collocated MIMO can be described through its distance between the different transmitter and receiver element as it is small compare to the distance between radar and the potential target [31]. On the contrary, statistical MIMO radar represents a wide separation of distance between transmitter and receiver in the radar topology for spatial diversity exploitation [31]. Fig. 4 illustrates a collocated MIMO radar [31].

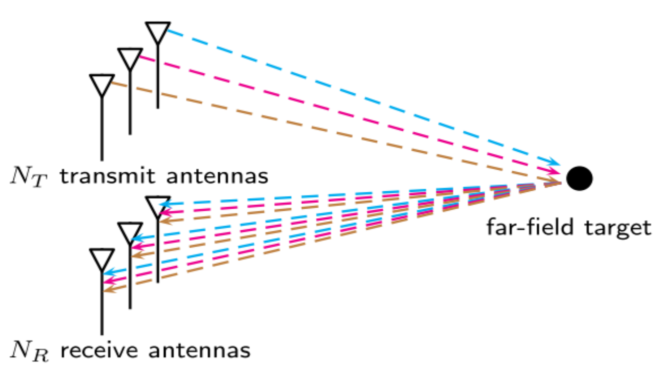


Fig. 4.Collocated MIMO radar has small separation between transmitter and receiver elements [31]

Hinz et al. contributed in MIMO area with regards to ship detection, through their exploration on the potential MIMO radar approaches in a High-Frequency Surface Wave Radar (HFSWR) [31]. Available bandwidth is known as the limiting factor in HFSWR; which is inversely corresponding to its range resolution [31]. Thus, in the research they extended existing SIMO FMCW to MIMO FMCW to reuse the limited HF radar band resources and also discussed on the possible methods for MIMO FMCW signals separation at receivers [31].

As a result from MIMO topology, multiple data are received from multiple sensors. [32] presented a concept supported by the algorithm on the multi-sensor decentralized data fusion for maritime targets tracking, focused on the shore-based radar [32]. The study proposed numerical estimation to be done by Kalman filter algorithm which assumed to perform well under linear condition in which vessels were moved on the same course for the long time; However, there was still an uncertainty for the algorithm to be used for targets tracking in harbor areas [32].

Meanwhile, in [33] an attempt was made to mitigate the issue occurred in a time domain multiplexing (TDM) frequency modulated continuous waveform (FMCW) which influenced the target's position detection due to different effects of motion. FMCW signal is commonly used in maritime environment due to its radar's dynamic requirements.

B. *Detection Techniques*

Difficulties arise in a radar system at a stage when it needs to distinguish between the useful target from the background interference. Thus, it requires a detection strategy to ensure useful signal component can be separated for further analysis and translates into beneficial information. To realize, it involves various aspects in system design starts from selection of system type and topology, waveform, detection mechanism at receiver, signal processing until how the information is displayed. The selection criterias are dependent on the application, in order to produce the best output out of the system. This section provides an overview of some recent studies with regards to various aspects in detection techniques.

1) *Forward Scatter & Back Scatter Systems*

- ***Forward Scatter.*** Fundamentally, a bistatic radar cross section (RCS) comprises three interesting regions in which are known as pseudo-monostatic, bistatic and forward scatter; which each is defines by the bistatic angle [27]. One of the recent focus exploration is on a forward scatter approach. Forward scatter region exists is at when the bistatic angle approaches 1800 which means FS radar (FSR) operates under a considerable narrow scattering area along the transmitter-receiver baseline [27] [28]. Fig. 2 (d) depicts the conceptual idea of FSR system.

Daniel et al. research was an example of an FSR system; which they presented a simulation of a buoy-mounted employing an FSR system to discover small, low cross section and low speed maritime targets [14]. The research concluded that maximum visibility of target is obtained under an optimum wind direction and boost with the incremental of antenna height over a range of sea states (wave height) [14]. However, the investigation required for further work with focused on (i) various target size, (ii) velocities and (iii) radar frequencies [14].

Kabakchiev et al. probed into the two main issues of maritime FSR system which were detection and estimation of low-profile marine target's length [28]. Through this study, they presented two forms of pre-processing algorithms based on the Local Variance Filtering (LVF) utilization, which were envelope and phase; to resolve the low signal-to-clutter ratio (SCR) problem and an algorithm for length estimation under the low SCR, by the assumption of known or previously estimated velocity [28].

There was also a comparative study done in [7] between an FSR and multistatic systems on small/ difficult maritime targets discovery, which in this particular research authors utilized an inflatable boat as a cooperative target. They reported that both systems were capable to detect a small vessel, but, each achieved via different approaches [7].

• ***Back Scatter.*** In most radar systems, backscatter radar (BSR) is the favorable since a way back. This type of technique utilizes the bounce back radar signal either from target or any reflector. Fig. 2 (d) also illustrates the conceptual idea of BSR system. [34] was a research worked at high frequency (HF) band utilized over-the-horizon radar (OTHR) which its operation is based on diffraction of electromagnetic waves. This type of radar uses either a ground wave or sky wave propagation for target detection; and offer greater detection range while compromising its' accuracy [34].

Hofele [35] in his paper analyzed the Probability of Detection on correlation between antenna's height and detection range in duct condition, adopting a BSR system of SPEXER 2000 Coastal Radar. SPEXER radars are first radar of this type to have at command AESA technology and the main task of this radar's family is to detect and track small targets such as human, small vehicle, small low flying airplane, small boat and swimmer [35]. Fig. 5 illustrates SPEXER 2000 coastal radar displayed an example of a back scatter system [35].

Fig. 5.SPEXER 2000 Coastal Radar on a tower obtained from Hofele's paper [35].

In year 2016, a comparison of backscatter radar data distribution to normal noise distribution or distribution of some clutter had been done by Prokopenko et al., in order to synthesize a decision making rule through their proposed algorithms for a slow moving target detection [36]. Their simulation result proved the developed algorithm was faster and more effective compared to classic MTI algorithm for slow moving target detection [36].

2) Selection of Signal

In radar design, waveform is selected based on its suitability to the application in order to optimize the performance. Fig. 6 summarized example of regular waveforms used in radar systems [37].

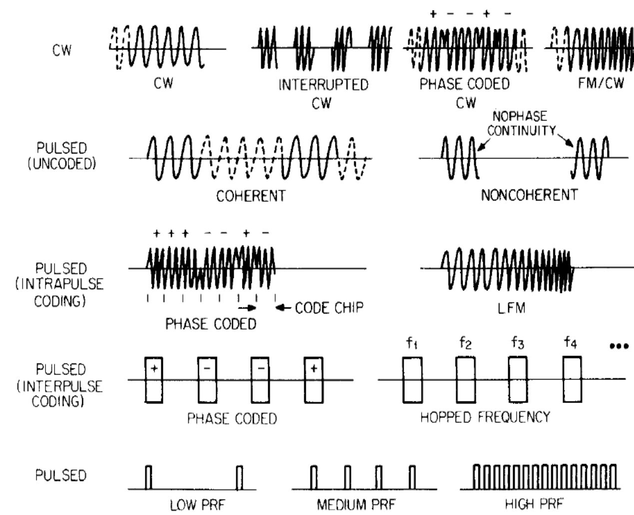


Fig. 6.Example of regular waveform used in radar systems [37]

The most frequent and widely waveform used is a repetitive train of short pulses due to shorter and more precise range [1]. However, a different type of waveform is being utilized such as a continuous wave (CW), frequency-modulated continuous wave (FMCW), pulse-compression and multiple pulse repetition interval, for more specific or targeted purpose [1].

[38] represents a research which explored a multi-channel low pulse repetition frequency (LPRF) signaling suitability for coastal and maritime surveillance in their proposed modelling architecture of scanning and non-scanning. The paper also provided trade-off analysis among the system parameters, environmental parameters and system performance [38].

However, a maritime environment has dynamic requirements, thus most radars implemented utilize FMCW type of waveform. Three main advantages of an FMCW radar system compared to a pulse radar which are (i) a constant power envelope, (ii) a high Doppler shift tolerance and (iii) the ability to use a simplified receiving processing [31]. In addition, this type of waveform also resistance to interception, compatible with simple solid-state transmitters compared to a pulse signal and provides a good range resolution [39]. On the other hand, some of its known issues are on (i) the signal leakage from transmitter to receiver (in case of monostatic) and (ii) range-Doppler coupling [31]. For FMCW analysis, a single sweep waveform is sufficed for a static target; While, sweep-to-sweep processing able to perform a moving target indication (MTI) and a moving target Doppler (MTD) [39].

On 2013, the author of [40] in his work had demonstrated a method to quantify Doppler Shift of a moving target. He took advantage of the FMCW signal characteristic that detection of the target range can be accomplished by processing the difference in the received signal shifting with reference to the transmit signal [40]. In the research such as [40] that implemented FMCW signal as the radar's transmission method, three approaches to analyze this type of radar which are [1]:

(i) Phasor diagram
(ii) Fourier analysis
(iii) Time-frequency plot

In this particular paper [40], the researcher employed FFT to obtain the Doppler Shift [40].

[41] in their vessel identification study based on vessel profile, also had chosen to utilize data from a high-resolution continuous wave linear frequency-modulated (CW-LFM) K-Band radar. It utilized an active correlation process that involved mixing the signal echoes with a replica of the transmitted signal, followed by a bank of filters and range information can be obtained by processing the mixed signals [41].

In another work [7], the study implemented FSR system which exploiting multi-frequency continuous wave (CW) radar. By adopting CW waveform, radial velocity can be obtained from the Doppler frequency shift [1]. Nevertheless, it was known that there is a limitation when involved long range and high resolution applications if a CW signal is realized via step-frequency method in MIMO radar[42]. The implementation required a waveform with a huge number of step-frequency and appropriate dwell time at each frequency, which resulted long intervals between updates and ensued difficulties in fast moving target Doppler processing [42].

3) Deteection Mechanism

Detection mechanism describes on how the target can be distinguished at the receiver end. Various techniques or methods can be applied based on the system requirement and suitability. High accuracy and quality of target identification can be obtained through a good detection mechanism. Thus, the signal processor needs to be configured and fine-tuned according to waveform used for optimum result [37]. There are numerous techniques for detection such as envelope detection, phase detection and others depending on the type of signaling and topology of the radar system.

Example of a detection mechanism, a radar system equips with a phase detector to extracts Doppler frequency by comparing the received signal to the reference signal (or transmitted signal) [1]. Other example is implementation of envelope detection to eliminate intermediate frequency (IF) and pass the modulation envelope, for a system where the signal envelope is in place [1].

Ummenhofer et al. in their work [10] on the Doppler estimation, utilized Orthogonal Frequency Division Multiplexing (OFDM) signal features over a Digital Versatile Broadcasting-Terrestrial (DVB-T) based passive radar system vessel-mounted. It is known that orthogonal transmitted waveforms able to enhance target localization performance in MIMO radars as it increases the decree of freedom and utilization of virtual array [43]. In case of [10], two stages mixer was implemented at receiver for its detection mechanism to prevent a back-folding subjacent OFDM channels which may cause an unacceptable increase of noise.

While, [44] in their research deployed a high-frequency surface wave radar (HFSWR) operated in HF environment moving targets with very low speed or non-moving targets. In HFSWR, detection and tracking of moving target is done by utilizing the Doppler shift of target [44]. Thus, the detection method proposed was to make use of zero-Doppler spectra of HFSWR echoes caused by targets radial movement relative to the radar site; which the spread characteristic of target echoes at zero radial velocity in the beam space is utilized to detect the target and this was experimentally validated and coincided with AIS data [44].

Dual HFSWR is known for its capability to continuously detect and track moving vessels also to overcome the negative effect of sea clutter [45]. A new target detection method based on a fusion Range-Doppler (R-D) image level was introduced by [45] for dual HFSWR, where they optimally utilized the multi-dimensional features of area target and linked the two-constant false alarm rate points of different frequencies to area target in the fusion image.

Stastny et al. applied corner reflectors on wooden canoes in space-borne Synthetic Aperture Radar (SAR) implementation, presented an improvement of the canoes' detection through their proposed method [9]. In this research [9], they indicated that by introducing high RCS corner reflectors on the target improved the detection by resulted (i) higher signal-to-clutter ratio (SCR) obtained at higher RADAR center frequency and (ii) canoes detectable with ease in X-band than in C-band under the similar resolution; research focus was on SCR and target detection minus the performance of detection algorithm.

In MIMO radar implementation, selection of signaling is crucial as a receiver need to have the detection capability to separate multiple waveforms from multiple sources. [31] in their study applied MIMO FMCW to a monostatic FMCW HFSWR focused on ship detection. In the paper, they laid out possible approaches for FMCW signaling and discussed on the pros and cons each approach which were (i) Dual-frequency/ multi-frequency FMCW, (ii) Time-staggered FMCW, (iii) Opposite-slope FMCW (iv) Different bandwidth FMCW.

As mentioned prior, all transmitted MIMO radar signals are necessary orthogonal to each other for detection and separation by receiver. In year 2014, Guetlein-Holzer et al. explored on TDM for MIMO FMCW which is the easy mechanism to separate the multiple signals from transmit antennas [33]. In the study, researchers investigated and analyzed on two TDM modulation schemes which were (i) the intertwined modulation scheme and (ii) the triangular modulation scheme; with regards to the effects occurred in the presence of relative motion between radar and target [33]. The effects impacted the detection of targets position and by applying the proposed methods, findings showed that both methods displayed their capability to estimate a two-dimensional target location and capable to deal with varies velocity [33]. However, it was also observed that a triangular modulation had slightly higher measurement time while intertwined modulation was slightly difficult to apply into a radar system [33].

Due to evolution of maritime radar into a moving platform environment, Erik et al. had done a study of moving-platform mounted sensor such as ship [46]. Target detection and tracking is no longer can be assumed its position and orientation when involved a moving platform [46]. Thus, in their work they had compared two methods to overcome the detection issue which were through implementation of Schmidt-Kalman filter and converted measurement approach [46]. Through simulation they proved that Schmidt-Kalman filter yields the best improvement in the term of consistency, and on the other hand, converted measurement yields better improvement in terms of root mean square error for the target tracking [46].

4) Signal Processing Algorithm

The processing algorithms derive functionality of signal processing and its ultimate goal is to have efficient algorithms for operations to deliver an almost non-time consuming nearly-ideal outcome. In a maritime environment, target's detection dependent on the target scenario, propagation medium and interference environment. Thus, maritime radar performance is highly dependent on how the system able to distinct between target over sea clutter received. Moreover, the propagation of transmitting signal from the existing shore-based radar, from land to the sea resulted in triangulated reflections from standing waves, which causing sea clutter spikes that severely affecting the quality of receiving signal [47][48]. Through signal processing, received signal is processed to extract the required information out of the system. Various exploration had been done by researchers on signal processing to improve system probability of detection which is a crucial element of maritime radar.

Kirscht et al. in their work reviewed in details on the algorithm issue encountered by particular maritime modes for (i) open-sea surveillance, (ii) maritime MTI and (iii) inverse SAR imaging of ships [2]. A testbed for advanced radar modes for this study was developed by using the existing Learjet 35 aircraft and SmartRadar by AIRBUS Defense and Space. A special Land-Sea Discrimination (LSD) algorithm had been introduced in open-sea modes fitted to the localization of the scanning operation of the radar which eliminated land detection since it was none of the radar processing's interest and to produce better result[2]. Besides, [2] also applied a Post-Doppler Space-Time Adaptive Processing (STAP) with regards to maritime target detection for maritime moving target indication (MMTI) modes. For MMTI, the time-domain data for each sub-aperture channel were first converted to the frequency-domain by a Doppler-FFT and the output of range/Doppler matrices were then processed in spatial-domain in the Post-Doppler STAP introduced [2]. Fig. 7 displayed the main processing steps for the MMTI mode [2].

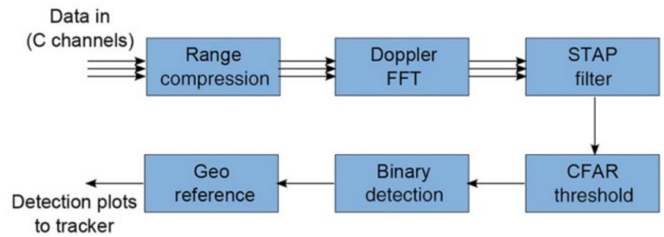


Fig. 7.Processing of MMTI mode [2]

Fig. 8 provides an example of Range/Doppler matrix before and after post-Doppler STAP filtering and displayed that the sea-clutter components were effectively cancelled which resulted a uniform background resembling white noise after post-Doppler STAP [2]

W.Sediono [40] on year 2013, in his paper explored a potential processing method to measure Doppler Shift of a moving target captured by maritime radar. Dual-FFT steps were applied which are (i) range FFT and followed by (ii) Doppler FFT on the target of interest; which proven to be able to determine the radial speed of a moving target through computer simulation and actual measurement using radar INDERA [40].

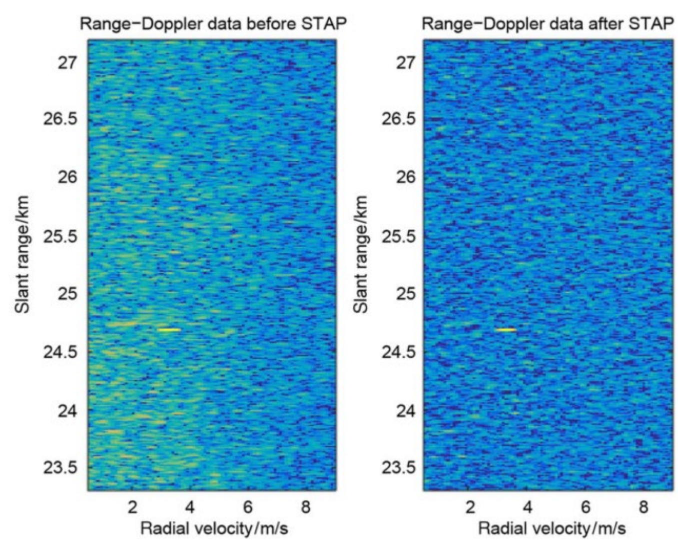


Fig. 8.Example Range/Doppler matrix before (left: sum-channel image) and after (right: sum-channel image) post-Doppler STAP filtering [2]

Other article written on signal processing algorithms development in maritime radar was by Stateczny and Kazimierski [32], discussed on two algorithms which were Kalman Filter and General Regression Neural Network (GRNN) in the aspect of data fusion – centralized and decentralized. Suitable fusion approach was identified by taking into consideration the three main issues of the fusion target from a multi-radar sensor which were (i) track association, (ii) coordinates transformation and (iii) measurements synchronization [32]. This paper concentrated on Kalman Filter as the basic algorithm with assumption it is well performed in a condition that vessel moved for a long period with the same path [32]. In addition, there was an uncertainty for algorithms to be used for target tracking in harbor areas which lead to the idea for future work on GRNN and even a hybrid of Kalman and GRNN [32].

A paper published on the 2016, [34] with the aim to propose, develop and test a multi-radar multi-target tracking algorithm for maritime surveillance at an over-the-horizon (OTH) distance. It utilized a weighted pure minimum-mean-square-error (MMSE) algorithm for multi-radar data fusion and adaptive alpha-beta tracking algorithm for tracking under high frequency (HF) and from simulation, the proposed algorithms displayed high reliability regardless its simplicity which yet to be tested over an existing HF radar network [34].

Research done by Scotti et al. on a photonic-based on a dual-band (S- and X-band) radar exposed new potential prospect for new advanced classification algorithms through its data fusion technique among the sparse channels without a heavy phase alignment process [21]. The proposed architecture shared a single transceiver and allowed generation and detection or radar signals done simultaneously [21]. Moreover, it permitted multiple target detection and also increased range resolution in a small vessel detection by merging data from these two bands [21].

In other paper, Johansen et al. did a simulation study, explored the prospective of the unmanned aerial surveillance system (UASS) as a mobile and elevated platform for sensors in the condition of hazard collision avoidance [13]. Feasibility study was done on key control algorithms based on receding-horizon optimization and concluded that the proposed approach seems workable and effective to support the collision avoidance for slow moving ships [13].

[28] work on the assumption that the variation of phase and amplitude in a Doppler signal signature inside a forward scatter is stronger than outside, had presented two processing algorithms based on the Local Variance Filtering (LVF) which were for envelope and phase; for a better low-profile (small and slow) marine target detection. The similar study also proposed an algorithm for estimation marine target length under a low signal-to-clutter ratio (SCR) with assumption of known or previously estimated velocity [28].

Recently, there were several tracking algorithms for multipath detection problem were proposed yet unable to cater a greater number of false alarm in maritime target detection [49]. Thus, Shen et al. investigated on the issue with regards of maritime target tracking at the presence of multipath effect in a Pulse Doppler (PD) radar. The multipath issue occurs when radar tracks a maritime target at a low altitude target on the sea surface, as the sea surface is capable of reflecting electromagnetic waves which produce the multipath effect causing the radar to unable detect target properly [49]. In this paper, they proposed a Multipath Bernoulli Particle Filter (MBPF) which the simulation resulted improvement in radar's tracking performance which they claimed faster and lesser error compared to an ordinary Bernoulli filter, yet still provided a good performance even with a large number of false alarm [49].

Above mentioned are some of the recent research done in the algorithms domain to enhance the maritime radar performance localized on targeted applications and environment. The following section will discuss on recent works in maritime radar imaging.

C. *Benchmarking and Improving Maritime Existing System Design*

There are huge contributions by many scholars to improve the performance of maritime radar in many aspects; inclusive (i) review/ comparative study on existing maritime radar system, (ii) improvement in antenna design for maritime radar application, and (iii) optimization of existing maritime radar system/ application.

1) *Review or Comparative Study on Existing Maritime Radar System.*

Collation of four operational vessel detectors which operate on satellite-borne SAR, with the goal to provide insights on the latest technological capacity in automatic ship detection which benefits from sensors' large swath widths and its robustness to operate during all weathers also daylight-night [15]. From analysis, it was concluded that all detectors were functioning well generally but none is entirely robust to the challenging scenarios set for the analysis tests, namely; SAR azimuth ambiguities, coastline effects, large target, sea clutter and side lobes [15]. However, each specific detector's drawback made them complementary and lead to a start point of a merging scheme implementation for improvement [15]. Table I provides the summary of four operational vessel detectors for maritime surveillance reviewed by the study [15].

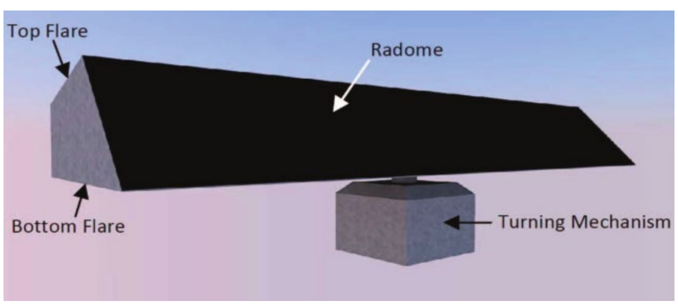
[2] reviewed the new maritime modes available in airborne SmartRadar by AIRBUS Defense and Space; Also presented was the result from the 2013/ 2014 flight campaigns. Algorithmic issues that had been pointed out in the paper has been explained prior under "Signal Processing Algorithm" section. Basically, the paper published had addressed the technical aspects of the newly developed mode which provide a good information on SmartRadar system improvement.

TABLE I
SUMMARY OF VESSEL DETECTORS [15]

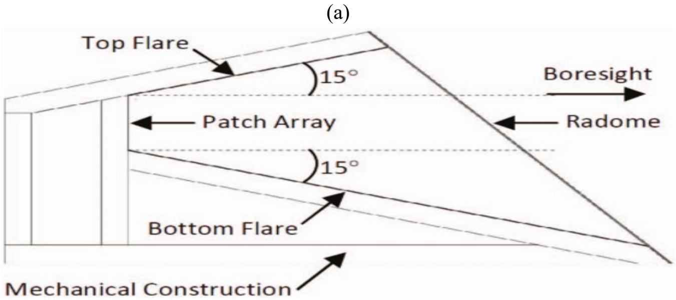
Name	Organization	Sensors supported	Land masking	Ship detection theory	Additional features
SUMO	Joint Research Centre, European Commission (JRC)	Envisat, ERS2, RADARSAT-1, RADARSAT-2, COSMO-SkyMed, TerraSAR-X	Shapefile with buffer zone	CFAR with K-distribution background	Azimuth ambiguities; Ships that are too long or too wide are rejected
SIDECAR	GMV Aerospace and Defense, S.A.U. (GMV)	Envisat, ERS2, RADARSAT-1, RADARSAT-2, COSMO-SkyMed, TerraSAR-X, ALOS-PALSAR	Shapefile with buffer zone; Shapefiles automatically extracted from image	Cluster-based approach based on Wavelet Transform (WT)	Azimuth ambiguities; Geodetic Active Contours to delineate target contour; Inclusion of target categorization with associated confidence
UPC-WT	Remote Sensing Lab (RSLab), Universitat Politècnica de Catalunya (UPC)	Envisat, ERS2, RADARSAT-1, RADARSAT-2, COSMO-SkyMed, TerraSAR-X, ALOS-PALSAR	Shapefile with buffer zone; Shapefiles automatically extracted from image	CFAR with Gaussian-distribution background based on WT	Azimuth ambiguities; Ships that are above or below a given size are rejected.
R&G	eOsphere Limited	Envisat, ERS2, RADARSAT-1, RADARSAT-2, COSMO-SkyMed, TerraSAR-X, ALOS- PALSAR	Shapefile with buffer zone	Median filters, to separate targets from background; Pauli decomposition channels for quad-pol	No Azimuth ambiguities; Histogram of the detected pixel for outliers and fitting an ellipse to the remaining detected pixels.

2) *Improvement in Antenna Design for Maritime Radar Application.*

There were also a great number of studies which focusing on the antenna for maritime radar applications. [50] probed into the application of asymmetric flares as an economical alternative for vertical beamwidth and sidelobes controls of a patch antenna for S-band maritime radar. The simulation justified that the used of flares meet the antenna requirements specifically for maritime radar at low cost [50]. Fig. 9 shown (a) a 3D illustration of the construction for the proposed antenna system and (b) a side view (cross section) of the antenna design with asymmetric flares.



(a)



(b)

Fig. 9.Proposed antenna system (a) 3D illustration of the construction, and (b) side view (cross section) of the antenna design [50]

Da Costa et al. in their work published on year 2015, proposed and analyzed a novel slotted waveguide antenna array structure which enable the antenna to operate over two frequency band; S- and C-bands [51]. This proposed design is suitable for communication, navigation and surveillance maritime radar applications [51].

[52] proposed a novel front-end architecture which advantages in the case of large antenna arrays with many active antenna elements were utilized specifically for civil navigation shipborne radar application. The proposed active electronically steered array (AESA) antennas architecture was intended as an alternative to existing linear mechanically steered array (MSA) antennas which proven high robustness and inexpensive [52]. Fig. 10 illustrates a sketch of a section of the proposed AESA antenna and Fig. 11 illustrates the functional sketch of the proposed AESA antenna [52].

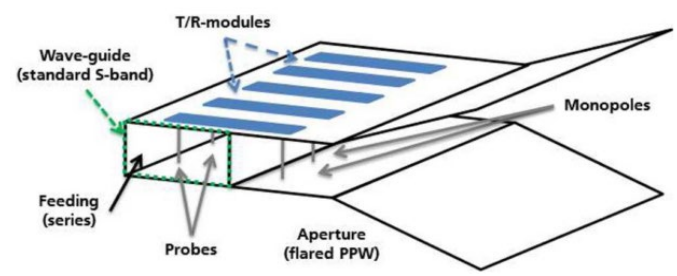


Fig. 10.Sketch of a section of the proposed AESA antenna. The conceptual design offers a compact, plain and inexpensive front-end [52]

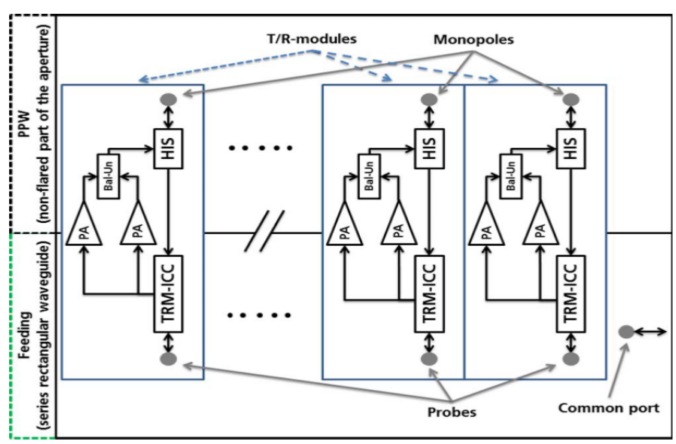


Fig. 11.Sketch of a section of the proposed AESA antenna. The conceptual design offers a compact, plain and inexpensive front-end [52]

3) Optimization of Existing Maritime Radar System/ Application.

Uchacz et al. presented an optimization model for a radar system in a vessel traffic system (VTS) on port water areas [53]. The idea was to identify proper location for radars to obtain the information about vessel traffic required. However, the proposed model was simplified and further development of the model through removing the limitation such as different ranges, different radar types, allow overlapping radar ranges and adopt the double criterion objective function; may lead to more reassuring result [53].

Non-stop studies with various focus of fields in maritime radar reflects the major radar role in marine applications and environment.

IV. Recent Techniques for Small Vessel Detection

Overall, previous sections reviewed on the work contributed by many researchers in multi-area of maritime radar development. Although this paper's focus is on the small vessel detection, by reviewing literatures in recent maritime radar provides the insight on small vessel detection can be improved. From literature also, it is well-known that detection of small vessels still an issue in maritime radar. This issue is due to maritime environment effect to the existing radar topology such as multipath reflection under the normal propagation conditions, the offing wind speed, the ocean flow, the smeary sea surface, the surface disturbance of high seas, the climate and others; which are unstable and non-gauss variable with time [54]. The above-mentioned factors, are causing the small target of sea surface almost submerge in the sea-clutter from radar echo energy in which the echo energy can't be accumulated as the sea-clutter is correlative [54]. The spectrum of target overlaps the spectrum of background as small target moves with sea waves [54]. This affect the radar system's probability of detection.

This section provides overlay on some recent attempts in maritime radar towards vessel/ target detection and is summarized in Table II. Some of the recent techniques that had been experimented and produce promising results were:

A. Hybrid FSR-Backscatter Systems.

A paper published in year 2015 by Ritchie et al. brought into play both FSR and BSR systems [7]. They utilized a multistatic radar system comprised three-nodes coherent pulse radar NetRAD by the University College London (UCL) together with multi-frequency CW FSR radar by the University of Birmingham, in their research on a small inflatable boat detection. It was the first recorded data utilized both radar types to allow a comparative analysis between both radars' detection performance towards small maritime targets [7].

B. Photonic Based System..

Laghezza et al. (2015) had done experiments to validate the first photonic-based radar (PHODIR) system demonstrator in a real maritime environment in compare to a commercial solid-state radar, SeaEagle by GEM elettronica. The target focused were on small ships and yachts which are categorized under a small profile target [22]. Its outcome was a promising alternative way towards flexible and high-performance radar.

C. Dual-Frequency Photonic Based System..

By utilizing PHODIR system, Scotti et al. (2015) enhanced the system to allow concurrent generation and detection of radar signals for S-band and X-band. The proposed system reduced the complexity and cost as both signal generation shared a single laser source as a multitone oscillator, preserved waveforms thus data fusion algorithm can be enabled without heavy phase alignment process [21]. At the receiver end, signals for both bands can simultaneously sampled and further digitized with a single analog-digital converter (ADC) [21]. Through merging the data from two frequency bands, resulted the proposed system to deliver better range resolution for a small vessel detection [21].

D. FMCW-MIMO Systems.

FMCW waveform is widely utilized in maritime radar and by employing MIMO topology produce more promising performance of the system. A paper [56], focused on the imaging during the berthing of a large ship in inclement weather due to its poor perceptibility. The issue can be overcome using the costly and heavy mechanical scanned system. Thus, Huang et al. proposed an FMCW MIMO radar utilized existing conventional components to produce a system of 4 transmitters and 16 receivers, which a possible option enhance to the image's resolution [56]. The diversity of transmit channels can be achieved by applying (i) time division multiplexing, (ii) frequency division multiplexing, (iii) spatial coding and (iv) orthogonal waveforms; However, in this study they employed a simple yet reliable method which is time division by switching transmit channels at different time slots [56]. Fig. 12 depicts the MIMO phased array radar system proposed in [56].

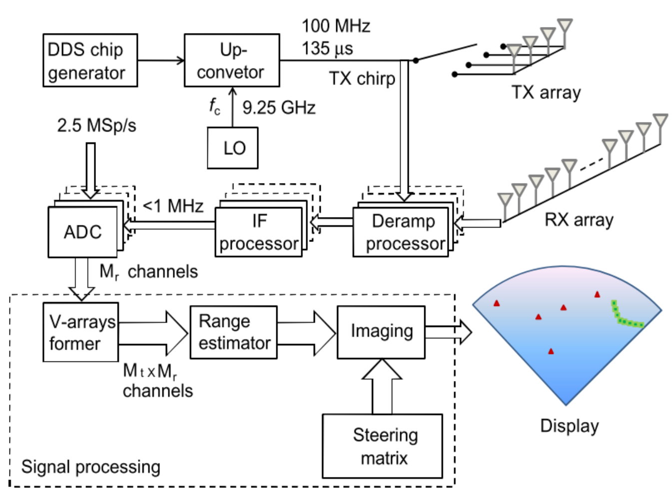


Fig. 12.Block Diagram of the Proposed MIMO FMCW Phased Array Radar System [56]

TABLE II
SUMMARY OF RECENT LITERATURES ON TARGET DETECTION BY MARITIME RADAR

Reference, Year	Type of Radar	Technique	Scope of Work	Waveform/ Operating Frequency Band	Radar Geometry	Topology
[7], 2015	Multistatic & Forward Scatter Radar (FSR)	Hybrid FSR-Backscatter System (Multistatic)	Detection performance of small maritime target - inflatable boat Method: Implemented 2 different radar setup (Multistatic & FSR) which operated in 2 different frequency bands.	Multistatic: Coherent Pulse/ 2.4 GHz (S-band) FSR: Multi-frequency continuous wave (CW)/ 7.5 GHz & 24 GHz	SIMO SISO	Multistatic: On-land FSR: On-land
[9], 2015	High RCS Corner Reflector & Space-based Synthetic Aperture Radar (SAR)	High RCS corner reflector	Detection performance of small maritime target – wooden canoes Method: Employed high RCS corner reflectors mounted on target with space-based SAR.	Linear FM/ X-band (TerraSAR-X/TanDEM-X & COSMO-SkyMed) Linear FM/ C-band (RADARSAT-2)	SISO	Space-borne
[10], 2015	DVB-T Passive Radar	Signal Processing for Doppler estimation	Detection of moving target Method: Development of Doppler estimation method using DVB-T standards OFDM	DVB-T OFDM/ DVB-T band (180-220 MHz)	SISO	Transmitter: On-land Receiver: Vessel-mounted
[12], 2015	Frequency Modulation Continuous Wave (FMCW) Radar	Signal Processing for Range Detection	Range detection of ISRA S-Band Coastal Surveillance Radar Method: Evaluation of Detection Range of ISRA S-Band Coastal Surveillance Radar	FMCW/ S-band (2.8 to 3.1 GHz)	SISO	On-land
[28]**, 2015**	Forward Scatter Radar (FSR)	Signal processing for Target Detection and Length Estimation	Target detection and length estimation Method: Introduced and applied two variances of pre-processing algorithms based on local variance filtering (LVF)	Non-modulated CW/ (7.5 GHz)	SISO	On-land
[22]**, 2015**	Photonic-based Radar	Photonic Based	Radar system performance and flexibility - in term of transmitted signal integrity and receiver pre/post-detection capability Method: New system architecture by implementing photonic transceiver	Modulated optical signal/ X-band (9900 MHz)	SISO	On-land
[18]**, 2016**	Synthetic Aperture Radar (SAR)	Sensor Fusion Radar-AIS	Maritime vessel target detection based on the fusion data from SAR and Automatic Identification System (AIS) Method: Simulation on joint implementation between SAR and AIS data.	Linear FM Pulse	SISO	Space-borne
[21]**, 2015**	Photonic-based Radar	Dual Band Photonic Based	Radar performance - increase range resolution for small vessel detection Method: New system architecture implemented a simultaneous generation of radar signal for S- and X-Band utilizing photonic transceiver	Modulated optical signal/ X-band (9875 MHz) & S-band (2459 MHz)	Dual-band	On-land

Prior in year 2011, there was a proof of concept done by Hinz et al. to compare the performance between time-staggered (TS) MIMO FMCW and a conventional phased array for usage in high-frequency surface wave radar (HFSWR) [57]. [57] displayed TS MIMO FMCW performance was comparable to the existing conventional phased array, besides it offered flexibility in antenna configuration and its simultaneous transmitter operation exhibited its prospective for mobile or space-limited FMCW HFSWR in the area of oceanography and maritime surveillance.

Due to FMCW MIMO is being the interest research area recently, thus, the following will provide brief description with regards of FMCW waveform on MIMO. For a FMCW MIMO system, it is best first to understand the FMCW waveform which is utilized for the system. The following equation represents a single chirp of an FMCW signal at a transmitter's end [31]:

$$S_{tx}(t) = exp\,(j2\pi(f_s t + \tfrac{1}{2}\alpha t^2)), \tag{1}$$

t indicates the time-variable within the single chirp period, f_s denotes the start frequency of the chirp and α for the sweep-rate, which is also equivalent to the ratio of bandwidth of the chirp (B) divided by the chirp duration (T).

The transmitted signal is then attenuated, delayed, and Doppler-shifted by a single target and reach the receiver which represent by the following equation a single non-moving point target [31]:

$$S_{rx}(t) = A.\ exp\ (j2\pi (f_s\ (t\text{-}\tau) + \tfrac{1}{2}\alpha(t\text{-}\tau)^2)), \qquad (2)$$

A indicates the attenuation factor and τ is the round-trip time of the signal to propagate to and from the radar system and target [31].

As for [31], the received signal is demodulated with the reference signal (transmitted signal) which then resulted the baseband. Then, the signal will undergo a stretch processing to eliminate the upper modulation which resulting the beat signal due to the difference in frequency, Δf [31]. The following equation represents the beat signal of a static point target [31]:

$$S_{if}(t) = A.\ exp\ (j2\pi (f_s\tau + \alpha t\tau - \tfrac{1}{2}\alpha\tau^2)), \qquad (3)$$

As for FMCW waveform range resolution, Δr and Doppler resolution Δf_D are as per following [31]:

$$\Delta r = \frac{C}{2B}, \qquad (4)$$

and

$$\Delta f_D = \frac{1}{NT}, \qquad (5)$$

C denotes the speed of light and N is the number of chirp.

Fig. 13 depicts an up-ramp FMCW in time-frequency domain in order to ease the understanding of this type of waveform [58].

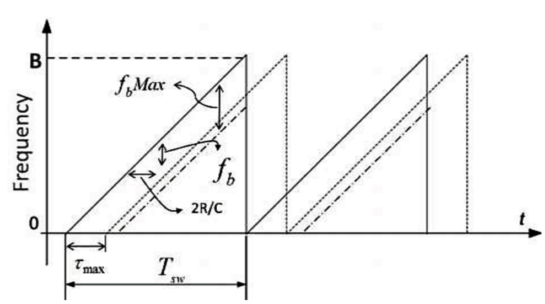


Fig. 13.Deramp processing of an up-going Linear FMCW (LFMCW) signal. The solid line represents the transmitted signal and dotted line represents received signal [58]

f_b *Max* indicates the maximum beat frequency, f_b is the beat frequency, τ_{max} is the maximum time delay for receiving an echo from a target, T_{SW} is a sweep time, R is a target range and C is the velocity of light [58].

However, upon deploying a MIMO topology over a FMCW system, a proper detection mechanic is required to distinguish signals received by receivers. Table III tabulates possible approaches for FMCW signaling pros and cons as per discussed in [31].

TABLE III
COMPARISON OF FOUR FMCW POSSIBLE SIGNALING APPROACHES [31]

Approach	Pros	Cons
I: Dual-frequency/ Multi-frequency FMCW	• The ability to distinguish the transmitted waveforms by frequency offset.	• Increase frequency separation between transmitted waveforms, receiver antenna spacing becomes suboptimal for receiving beamforming. This may either result in a small aperture or the introduction of grating lobes. • Also, require additional licenses to operate in more frequency bands.
II: Time-Staggered FMCW	• The ability to distinguish the transmitted waveforms by the time offset.	• Time offset between elements has to be larger than maximum round-trip time, τ.
III: Opposite-Slope FMCW	• The ability to occupy the same frequency band and time duration. • RF chain and the antenna spacing are optimal. • No additional license for a frequency band is required.	• Limited to two transmit signals.
IV: Different Bandwidth FMCW	• The ability to occupy the same frequency band and time duration. • RF chain and the antenna spacing are optimal. • No additional license for a frequency band is required. • Can extend to more than two transmit signals.	• Worsen the range resolution on the waveform with lesser bandwidth

Fig. 14 illustrates the four concepts of MIMO FMCW signal separation techniques to ease the understanding [31].

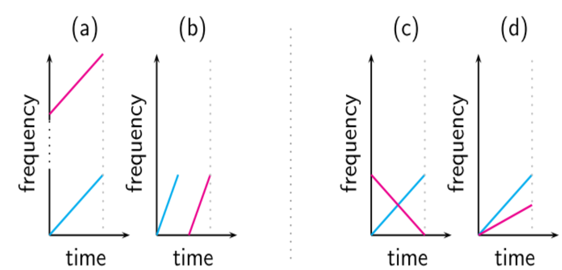


Fig. 14.MIMO FMCW – four possible signaling concepts (a) Dual-Frequency (b) Time-Staggered (c) Opposite Slope, and (d) The Same Start Frequency and Duration, Different Bandwidth and Slope [31]

V. CONCLUSION AND POSSIBLE FUTURE WORKS

In this article, we have presented a comprehensive review on the recent techniques focusing several aspects in maritime radar; (i) system topology, (ii) radar waveforms, (iii) detection algorithms, and (iv) other works done on benchmarking and improving existing radar system. From literatures, we noted that small vessel detection is still an open issue yet continuously being explored by many scholars on how to mitigate the problem.

Numerous techniques were discussed and acknowledged; each advantages and disadvantages. Further exploration in a wideband system is a potential method for a small vessel detection. Wideband radar is known due to its higher information measure of recognition, better secrecy, electromagnetic compatibility and robust to both active and passive interference [59][60][61]. In addition, it might be useful in localization target with significantly small and fluctuating RCS [25]. There were several recent attempts with regards to UWB FSR in maritime [62][63][64]. Therefore, it is essential that research of wideband radar system continues in order to improve maritime applications.

Additionally, the conceptual idea for an unmanned aerial surveillance system (UASS) as a secondary sensor platform had demonstrated its effectiveness for collision avoidance through a simulation study by Johansen et al. [13]. On the other hand, literature reported that by implementation of MIMO radar; it can improve number of detectable target, resolution and robustness against radar cross section (RCS) fluctuation [25][43][65]. Moving radar platform offers a flexible radar's area coverage besides reducing land-to-sea propagation which contributing to sea clutter. Thus, emergence of ship-borne MIMO is one of the possible method which we believe may offer versatility of the detection system is yet to be investigated.

Recently, many telecommunication systems or applications are adopting Artificial Intelligent (AI) to assist users for more effective handling. There was a paper written on AI technique in navigation decision-making which determine a ship's trajectory for collision avoidance [66]. Thus, we foreseen AI as an opportunity for a small vessel detection enhancement by having a radar system to be equipped with the capability to evaluate its current maritime environment and adaptively control its detection parameters to fit the condition. This may result for the optimum system's resources utilization and improve the detection mechanism for a small vessel. This possible technique is an enticing prospect yet to be explored.

ACKNOWLEDGEMENT

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