Synthetic Range Profiling, ISAR imaging of sea vessels and feature extraction, using a multimode radar to classify targets: initial results from field trials

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Abstract—**This paper describes the design and working principles of an experimental multimode radar with a stepped-frequency Synthetic Range Profiling (SRP) and Inverse Synthetic Aperture Radar (ISAR) capability for the purpose of operator-based classification of small to medium sized sea vessels in littoral condition. The experimental multimode radar is based on an experimental tracking radar that was modified to generate SRP and ISAR images in both search and tracking modes. The architecture and functionality of the experimental system is described. Initial results from field experiments are presented to demonstrate the functionality of the system.**

Keywords-Synthetic Range Profiling; Inverse Synthetic Aperture Radar; feature extraction, maritime classification; multimode radar;

I. INTRODUCTION

Over the last five years, the Council for Scientific and Industrial Research (CSIR) in Pretoria, have deployed measurement radars along the south-west coastline of South Africa to measure sea vessels and sea clutter for maritime surveillance purposes. These measurements were used to develop robust techniques towards detection and tracking, imaging and classification of sea vessels, as discussed in papers by Herselman, Baker and de Wind [1] and Abdul Gaffar, Nel and Inggs [2].

However, the datasets for classification purposes were all obtained when the radar was in tracking mode. In order to understand the requirements of the wide area maritime surveillance radar, an experimental tracking radar was modified into an experimental multimode radar with the capability of measuring sea vessels in both search and tracking modes. The datasets were used to generate Synthetic Range Profiles (SRP), Inverse Synthetic Aperture Radar (ISAR) images and extract features for maritime classification.

New building blocks were inserted into the tracking radar to modify it into an experimental multimode radar. A track-while-scan (TWSP) and a maritime classification processor (MCP) were added to perform the functions of detection and tracking, and target classification respectively.

The MCP used stepped frequency radar waveforms, discussed in Wehner [3], to generate SRPs. In this technique, multiple pulses are used to synthesize a large bandwidth transmit signal and motion compensation is required to prevent migration of scatterers due to the motion of the target over this interval. Furthermore, calibration is required to transform the radar's frequency response to be flat in amplitude and linear in phase to generate SRPs with a superior spurious free dynamic range (SFDR) to typically greater than 30dB.

ISAR is a radar signal-processing technique that uses the rotational motion of an object to generate a 2-D image, as described in [3]. It is challenging to generate focused ISAR images of sea vessels, because the 3-D rotational motion affects the presentation of the vessel in the ISAR image and it also causes blurring in many ISAR images, as shown in [2].

SRPs and ISAR images contain a rich source of information for classification, as shown by Bon, *et al.* [4], Yuan and Casasent [5] and Musman, Kerr and Bachmann [6]. Currently, the MCP automatically generates SRPs and ISAR images. These results are presented to an operator that performs feature extraction and classification, using a database of known vessels.

This paper describes the modifications made to an experimental tracking radar to provide it with the capability of generating SRP and ISAR images in both search and tracking modes, for classification purposes. This work addresses the challenges and makes a contribution towards imaging and classifying small boats. This was a joint development, by the Radar and EW group at CSIR, South Africa and the ECP programme at King Abdul Aziz City for Science and Technology (KACST), Saudi Arabia. Results obtained from field trials in Cape Town are presented.

II. THE EXPERIMENTAL TRACKING RADAR

The X-band, pulse-Doppler tracking radar, which was modified, was carefully chosen to have sufficient bandwidth to generate high-resolution SRPs of better than 1m. Furthermore, the radar's frequency response was adequately characterized to ensure that SRPs with a SFDR of greater than 30dB can be achieved.

The authors would like to express their gratitude to the National Program for Electronics, Communications and Photonics at the King Abdulaziz City for Science and Technology for supporting this work.

The experimental radar employs monopulse tracking using a pencil-beam antenna radiation pattern in the sum channel. One of the desirable properties of the radar is that the following radar waveform parameters are fully programmable: Pulse Repetition Interval (PRF), pulse code, number of pulses in a burst. Various waveforms were designed in order to measure sea vessels of different sizes. This is discussed in more detail in Section IV.

III. ARCHITECTURE AND FUNCTIONALITY OF THE MCP OF THE MULTIMODE RADAR

The multimode radar uses the TWSP and the MCP to perform the functions of detection and tracking, and classification of operator-selected tracks, respectively.

The building blocks of the MCP and the external interfaces are shown in Figure 2. The track information was obtained from the sensor fusion system (SFS), which contains track information from multiple sensors, via the SFS interface controller.

The TWSP and the MCP make use of the same radar's resources for measurement purposes. The Resource Scheduler (RS) is responsible for servicing requests from the two processors regarding transmit waveforms, scan rates and the measurement sector. Information is passed from the MCP to the RS via the RS interface controller. The RS is also involved with ensuring that the desired waveform is transmitted at the correct range and azimuth, as the antenna scans over the search sector and recording radar data. Once a radar recording is made, the RS inserts this information into the MCP local database. A detailed description of the TWSP and resource scheduler is outside the scope of this paper.

When radar data is processed, the pre-processor uses the waveform parameters to automatically detect and correct errors in the data and re-structures the data for SRP processing.

The core processing blocks of the MCP consist of the HRR processor, ISAR processor, feature extraction processor and the classification processor, which are responsible for generating motion compensated and calibrated SRPs, cross-range scaled focused ISAR images, providing tools for operator-based feature extraction, and operator based maritime classification, respectively.

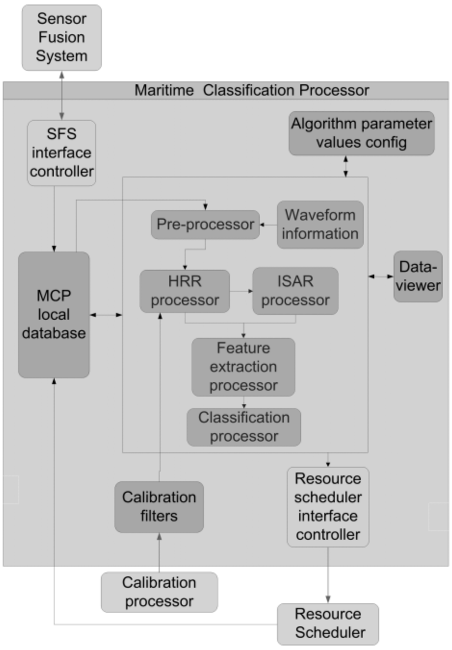


Figure 2: Simplified block diagram of the MCP showing both the internal building blocks as well as the external interfaces

The processing parameter values are stored in a configuration file, which can be modified by the processing operator. The calibration processor is responsible for generating the calibration filters, which is used to obtain SRPs with superior SFDR of greater than 30dB. Lastly, the data viewer is used to illustrate the processed results to the operator.

The computing hardware that was used to realize the MCP had the following properties: Intel I7 quad core @ 1.7GHz processor, 4GHz of RAM, 4 LCD screens and a multi-seat configuration via third party software.

The high-level functional flow diagram of the MCP is shown in Figure 1. The functions 1.0 to 4.0 involves obtaining operator-selected track information, sending the related information to the RS to transmit the desired waveform and record the related radar data, and transferring the recording to the MCP.

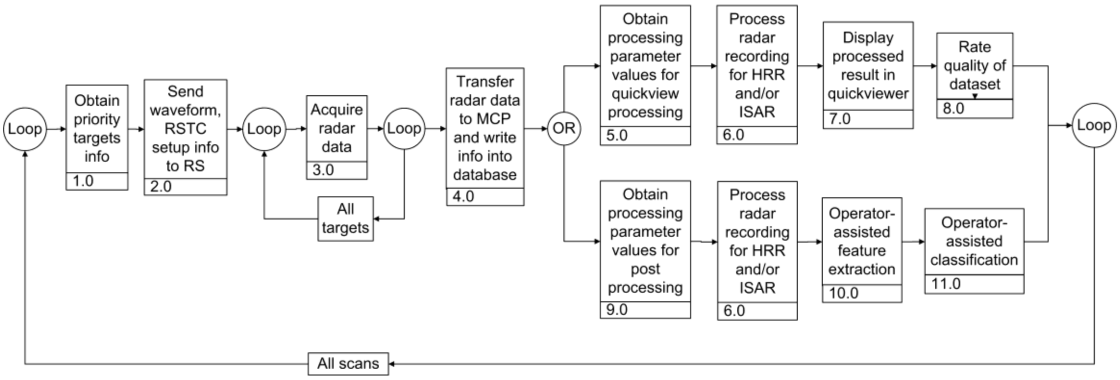


Figure 1: First level functional flow block diagram of the MCP

Figure 3: Photo of the experimental multimode radar and support containers deployed at Simons Town

Thereafter, functions 5.0 to 8.0 describe the quickview process, where the radar data is processed and displayed to an operator that rates the quality of the dataset. The good quality datasets may be processed later by the operator, which is described in functions 9.0 to 11.0, where SRPs and ISAR images are displayed to the operator to perform operator-based feature extraction and classification.

IV. MEASUREMENT TRIAL OVERVIEW

The main objectives of the trial was to obtain measurements of cooperative and non-cooperative sea vessels, in different environmental conditions, to support research into maritime classification as well as to demonstrate the functionality of the MCP in the search and tracking modes of the experimental multimode radar.

The experimental multimode radar was deployed at Simons Town, Cape Town at location 34°12′3.05″ S, 18°26′55.26″ E, approximately 110m above mean sea level during September/October 2010. The deployment site, shown in Figure 3, was chosen to setup a 90° search sector over False Bay with an observable range of 3km to 40km.

Over 400 radar datasets of cooperative and non-cooperative vessels, examples are shown in Figure 4, were obtained during the deployment. Various experiments were done to obtain datasets in search and tracking modes for research into imaging and classification. Cooperative vessels were instrumented with an Inertial Navigation System (INS), shown in Figure 4 (b), and a Global Positioning System (GPS) to record the vessel's translational and 3-D rotational motion over time.

Stepped-frequency waveforms were used to measure vessels of different sizes and the properties of these waveforms are summarized in Table 1. These waveforms made it possible to measure small vessels from 6m in length, to large vessels up to a length of 70m.

Table 1: Summary of waveforms used during the trial

Waveform number	**Properties of the stepped frequency waveform**		
	Unambiguous range [m]	***Range resolution [m]***	***Effective Pulse Repetition Frequency [Hz]***
450-452	75	1.13	[172, 152, 131]
454-456	30	0.47	[196, 173, 149]
462-464	15	0.47	[385, 340, 294]
869-874	[15 18.75]	0.26	[86, 114, 136, 136]

The range resolution was chosen so that there is at least 20-25 bins of target energy in the resulting HRR profile and this information can be used to aid with maritime classification. Waveforms with different PRFs were chosen so that their blind zones do not overlap and measurements would typically be performed with highest PRF waveforms where the vessel is not in the blind zone. Measured ISAR images of different sizes of boats from the literature [2],[5], as well as previous experience images and tools developed at the CSIR, were used to choose the minimum effective PRF, so that it is greater than the typical Doppler bandwidth of a vessel at sea.

V. RESULTS

This section discusses and presents initial results from sample datasets from the trial, which includes the following processing: calibration, generating SRPs, cross-range scaled ISAR images, feature extraction and maritime classification.

A. *Calibration*

In order to generate SRPs with a superior SFDR of typically greater than 30dB, the radar's frequency response is desired to be flat in amplitude and linear in phase. Unless designed as such, most radars do not possess this characteristic and deviation from this ideal response induces side-lobes in the SRPs. A characterization of the radar used showed that the most non-ideal components of this radar were the synthetiser and the RF-front end.

(a) (b) (c)

Figure 4: Photos of a few boats and equipment used during the trial: (a) Umoya Omusha, a cooperative sailing yacht, (b) the ADU5, 4-GPS receiver attitude measurements system, (c) a cooperative Rubber Inflatable Boat (RIB)

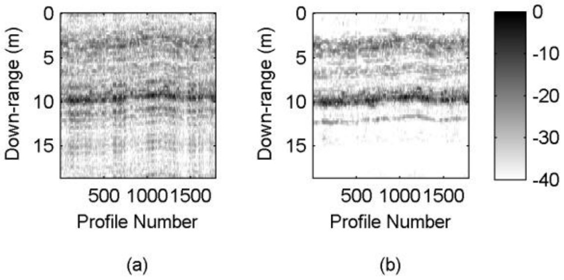


Figure 5: Motion compensated SRPs of the Umoya Omusha (a) before calibration, and (b) after calibration

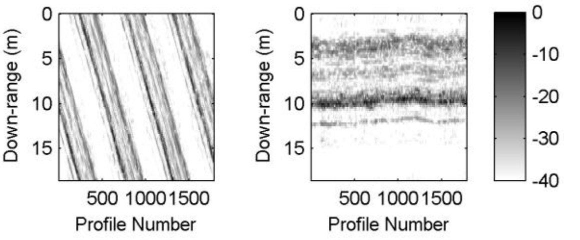
A high sampling rate digital scope was used to characterize the synthesizer and an Optical Delay Line (ODL) was used to analyse the RF-front end of the radar. Calibration filters obtained from these two processes were combined to form a single calibration filter, which was used to transform the radar's response to be flat in amplitude and linear in phase for a single point scatterer.

The results of applying the calibration filter to measured, motion compensated SRPs of the Umoya Omusha are shown in Figure 5. It is clear from these results, that the SFDR of the SRPs are significantly improved when calibration is applied.

B. SRP and Motion Compensation: tracking mode

The process of generating SRPs involves transmitting a sequence of pulses where the center frequency increases linearly using a fixed frequency step. The frequency step is chosen so that the unambiguous range of the SRP is greater than the projected length of the vessel. The SRP can be obtained by simply applying the Inverse Fourier Transform (IFT) to the range bin with the target energy for each transmitted pulse.

However, it takes a number of pulses to form a single SRP, and the motion of the vessel over this interval causes scatterers to migrate through high resolution range bins in the SRPs. Motion compensation for SRPs is discussed in detail in [3].



(a) (b)

Figure 6: Calibrated SRPs (a) before motion compensation, and (b) after motion compensation

The Radon-based algorithm, proposed by Martorella, Berizzi and Haywood [7], was used to estimate the vessel's velocity using calibrated SRPs. The velocity estimate was used to generate a motion compensation factor, which was applied to the measured data to prevent migration of the scatterers due to the motion of the vessel. The results of generating motion compensated SRPs are shown in Figure 6, where the effect of the translation motion of the vessel over the dataset has removed.

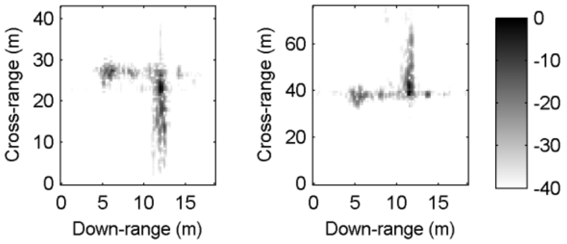
C. ISAR Processing: tracking mode

The signal processing steps involved in generating focused ISAR images are translation motion compensation, selecting focused ISAR images from a sequence of images and applying cross-range scaling to each focused 2-D image to obtain radar images defined in down-range and cross-range.

Translation motion compensation is typically done in two steps: range alignment and autofocus. The range alignment algorithms that have been implemented in the ISAR processor are the Haywood [8] and the Global Range Alignment (GRA) [9] techniques. The autofocus algorithms that were implemented were the Dominant Scatterer Algorithm (DSA) [8] and Yuan's autofocus technique [5]. The algorithms in [8] are well suited to targets with a single dominant scatterer and algorithms in [5] and [8] to targets with multiple dominant scatterers.

The optimum imaging selection algorithm proposed by Martorella and Berizzi in [10], with minor modification, was implemented in the ISAR processor. The modification included changing the formulating of the image contrast to ignore the range-Doppler cells around the zero Doppler bin, so that the focused images contain a target with a Doppler bandwidth, which is useful for classification. Secondly, multiple initial Coherent Processing Time Window Length (CPTWL)s were used to ensure that the algorithm finds varying lengths of optimum CPTWLs.

The optimum imaging intervals selection algorithm was applied to a 30s recording dataset of the Umoya Omusha sailing outbound with respect to the radar, which was in tracking mode. Two of the focused side-view images are shown in Figure 7. The cross-range scaling algorithm by Martorella in [11], was used to transform the cross-range axis from Doppler to range. It is clear that these radar images contain useful information, which can be used for classification.



(a) (b)

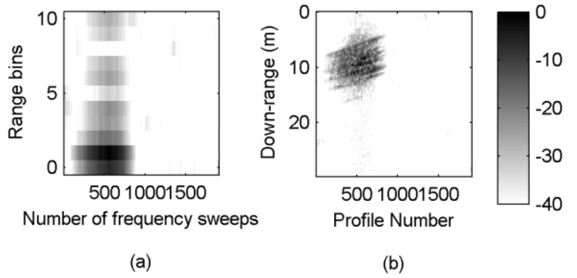
Figure 7: Focused, cross-range scaled ISAR images of the Umoya Omusha, (a) CPTWL = 1s, (b) CPTWL = 1s

D. SRP and ISAR: search mode

Measurements of vessels were also performed when the multimode radar was in search mode. In this mode, the MCP submits a request to the RS to transmit a stepped-frequency waveform as the radar beam passes over a stable track of interest, and to make a recording of this data.

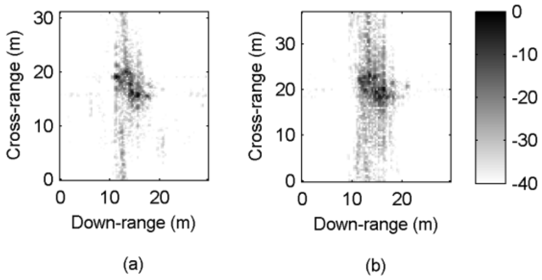
Typical results from a dataset of the rubber inflatable boat (RIB) (see Figure 4 (c)) in this scenario are shown in Figure 8. The MCP used this dataset to generate SRPs. The results clearly show that the vessel is in the recording between profile number 50 to 750. The SRPs may be displayed to an operator to estimate the projected length of the vessel, in order to choose a more optimum stepped-frequency waveform when this vessel is measured in future scans.

In this dataset, the dwell time on the target was set to be greater than 4s and ISAR processing was applied to find the focused ISAR images of the vessel. Two of the focused images that were found are shown in Figure 9. Over these intervals, the RIB was turning and an outline of the vessel can be clearly seen in the image. The richness of information contained in the SRPs and ISAR images can provide an operator with a recognized view of the stable tracks in the area under surveillance. By observing this sea vessel for a long time, the behavior can be observed and this can be used to estimate intent.



(a) (b)

Figure 8: Measured radar data of a small RIB in search mode, (a) Coarse range lines per frequency sweep and (b) calibrated SRPs



(a) (b)

(b)

Figure 9: Focused, cross-range scaled ISAR images of the RIB, (a) CPTWL = 0.7s, (b) CPTWL = 0.5s

E. Operator-based feature extraction

In the feature extraction processor, a set of user-driven and automatic tools have been implemented to extract features from SRPs and ISAR images. In this process, the operator chooses the threshold level relating to the ISAR image and the vessel outline. Thereafter, the centerline, number of masts and mast height(s) and length of the centerline are automatically extracted. The operator has the choice to modify the automatically extracted feature values. The understanding of the key discriminate features for maritime classification is part of future research.

F. Operator based classification

The local database of the MCP contains feature information relating to 135 vessels in the Simons Town area. Typical features are the length, width, number of masts, maximum speed and class of vessel. A histogram showing the different classes of vessels in the database is shown in Figure 10.

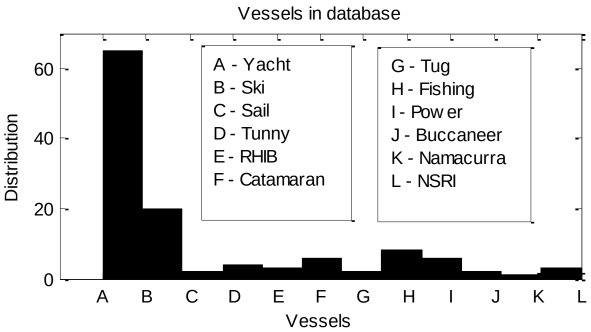


Figure 10: Histogram of different classes of sea vessels in the database

After feature extraction, the operator queries the database with the extracted feature values. The photos of the vessels that matches this search criteria is display to the operator and based on all the information gained, the operator chooses a classification category for this vessel with a confidence level. In this way, each track on the maritime surveillance display is classified.

VI. CONCLUSION

This paper described the modifications made to an existing tracking radar to provide it with the capability of generating SRPs and ISAR images in both search and tracking modes, for classification purposes. An overview of the measurement trial in Cape Town was given, where measurements of various sizes of vessels, in different environmental conditions were made, to demonstrate the functionality of the modified radar, and to obtain datasets to support research into maritime classification.

Initial results showed that the experimental multimode radar successfully generated SRPs and ISAR images of vessels in both search and tracking modes. These results were displayed to an operator that performed feature extraction and classification to provide the commander to a recognized view of the tracks shown on the maritime surveillance display.

ACKNOWLEDGMENT

The authors acknowledge the CSIR team involved with the measurement trial, specifically P. Barlow, A. Stanton, V. Jansen van Rensburg, J. de Witt, R. Berndt, L. Wabeke, S. Govender, C. van Zyl, L. Baben, A. le Roux and F. Anderson.

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