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MIMO Radar Simulation Using Simulink

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Abstract

This paper describes a Simulink-based software testbed, which was developed to aid our research on various Multiple-Input Multiple-Output Radar (MIMO radar) technologies designed to operate under different environments. The testbed was used as a platform to test the performance of new generation MIMO radars in detecting slow moving targets on the surface of the ocean. The performance of the developed testbed has shown many improvements over conventional phased array radars such as the ability to detect the targets faster and maintain a greater refresh rate of the surface radar picture.

1. Introduction

A navy ship must be able to accurately detect closely spaced surface targets in a cluttered environment for collision avoidance as well as to combat threats such as fast attack craft, submarine periscopes or wave gliders. Detecting surface targets becomes increasingly difficult when there are multiple threats inbound from different bearings or when a higher sea state is present. Current technology employed in many navies around the world for surface target detection is an active phased array radar or a rotational navigation radar. Although accurate, phased array and navigational radars suffer from the requirement to rotate their antenna base or electronically scan to search an area whereas a MIMO radar can search an entire area in only a few simultaneous orthogonal pulses [1]. Using a radar that can provide the same or better level of accuracy while providing a greater refresh rate is advantageous. However, a MIMO radar transmits with less directional gain, thus less energy will reflect off the target. To maintain the same probability of detection as a phased array radar, a MIMO radar must integrate the returns over several pulses [2].

Related previous work such as [3,4], discuss the advantages and short comings of MIMO radar and how it compares to a phased array radar. For instance, consider M transmitting elements and receivers for both a phased array and MIMO radar. In this example, the phased array radar would transmit with gain M times larger than a MIMO radar and would require M less matched filters to process the received signal. To maintain the same level of signal-to-noise (SNR) ratio as the phased array radar, MIMO must integrate its returns over a coherent processing interval (CPI) M times longer than a phased array. For a small search area, a phased array radar will be superior to a MIMO radar due to its inherent increase in gain and lower integration time. However, if the search area is large, such as a dedicated 90° sector for a phased array panel on the side of a ship, then a MIMO radar can be superior in detection time and picture refresh rate. This is true so long as the required CPI and processing time of the MIMO system is less than the scan rate of the phased array radar. Many fundamentals of MIMO radar are not covered in this paper, but references such as [5,6] are an excellent resource should one be required.

The goal of the simulations was not to determine if MIMO radar could replace a traditional phased array, but rather investigate how it could complement an existing radar suite onboard a naval ship. Consequently, the simulated MIMO system was designed for use with a colocated antenna scheme to determine if MIMO radar processing could be used with an existing phased array infrastructure on a naval ship. Using the existing hardware infrastructure on a ship is critical from a cost and implementation perspective, as significant upper deck refits are rare. Surface targets were chosen as the primary target of interest for two reasons. Firstly, ocean surface targets move at considerably lower speeds, 10-15 m/s, than air targets, 50 m/s and above. As mentioned, MIMO requires a longer CPI to detect the same target as a phased array. Fast moving and high accelerating targets such as missiles or aircraft introduce limitations on integration times [7], which could prevent detection. Secondly, examining surface targets minimizes the variables of the targets and limits the maximum detectable range of the radar to the radar horizon.

2. Simulink Implementation

Although two simulated radar systems were created, this section will focus on the MIMO radar system. Figure 1 illustrates the high-level schematic of the Simulink based MIMO radar system. The radar has six independent transmitters and receivers allowing for a 6x6 MIMO radar. Each transmitter and receiver are independent of one another and the spacing between transmitting and receiving elements is adjustable to the desired space of the user. The transmit and receive elements can be configured to create a monostatic or a bistatic radar system. A two-way MIMO channel was modeled using independent Simulink's LOS channel blocks from the transmit antenna array to the targets and from the targets to the receiving antenna array.

Various orthogonal waveforms can be implemented and investigated by the simulation. In this paper, Zadoff-Chu

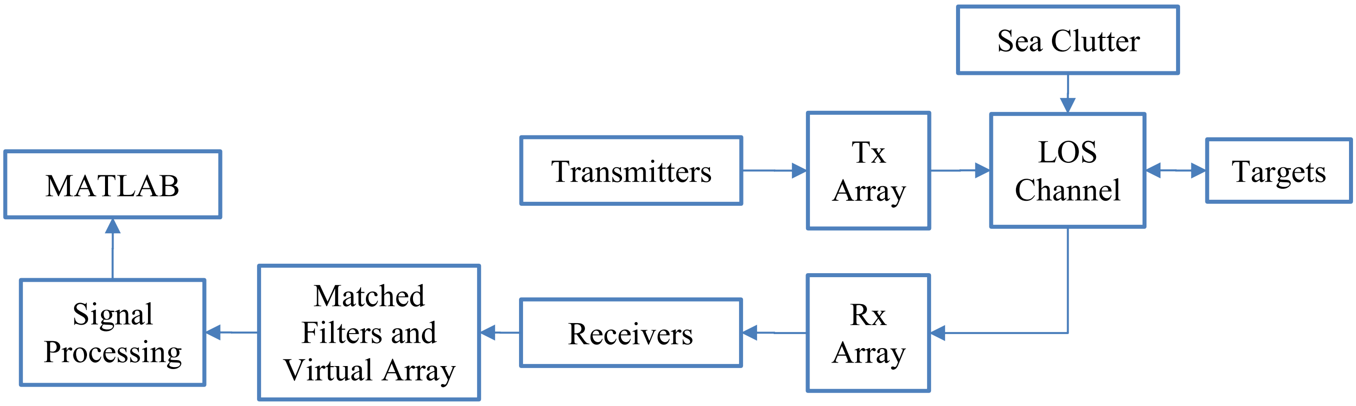

Figure 1. Schematic of Simulink-based MIMO radar simulation.

[8] phase encoded waveforms are used with time division multiplexing (TDM) to achieve orthogonality. Each waveform is transmitted from each element of the array at different times and separated by a pulse repetition interval (PRI) associated with a desired unambiguous range. Using six transmitting elements with TDM eliminates the use of matched filters that would be required for simultaneously transmitted orthogonal waveforms. Conversely, as a tradeoff for using less matched filters, TDM-MIMO radar will take six times longer to survey the same search area when compared with a MIMO radar using simultaneously transmitted orthogonal waveforms. On receive, because TDM is used, there is no cross correlation between the received waveforms. The transmit to receiver channel paths are known for each pulse that is sent and can therefore be directly mapped to an associated virtual array element.

The transmitting and receiving elements are adjustable to any antenna type. Either a preloaded antenna from the Simulink library or a custom built one with a specific antenna pattern can be used. The simulation accounts for antenna gain for each channel. Furthermore, each transmit and receive channel can be individually turned on or off, which in turn will adjust the spatial convolution of the received virtual elements, and change the two-way MIMO antenna pattern. Consider a monostatic antenna configuration with six elements separated by half of a wavelength to form a uniform linear array. With all six channels being used on transmit and receive, the MIMO two-way antenna pattern will consist of a total of 36 transmit and receive channels with the following distribution: [1 2 3 4 5 6 5 4 3 2 1]. This weighting creates an 11-element virtual array with half wavelength spacing that is used in all subsequent signal processing. The resultant two-way antenna pattern is shown in Figure 2.

It is also important to highlight that any number of targets can be simulated. Radar cross section (RCS) values and Cartesian positional coordinates are the minimum inputs required to simulate a target. Targets can also be provided with a three-dimensional velocity vector to simulate movement as well as be provided with updates to have the RCS fluctuate following a Swerling model. Backscattering models of specific targets can also be incorporated into the simulation.

The signal processing section of the simulation uses radar processing techniques commonly found in a phased array radar such as coherent integration, sensitivity time control, constant false alarm rate (CFAR) threshold detector, and narrowband phase shift beam formers. Space time adaptive processing techniques such as Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), Multiple Signal Classification (MUSIC), PARAFAC, and Capon were not implemented in this preliminary design, but could be easily incorporated in the future. The output of the signal processer is sent to a MATLAB workspace where the data can be manipulated and graphed.

3. Sea Clutter

Lastly, as the primary target of interest for detection is a boat on the ocean, there is a requirement for the simulation to include sea clutter models. The Naval Research Laboratory, Washington, DC published an excellent report on various emperical sea clutter models in 2012 [9]. The report examines and compares the models with a recommended approach of their own through through a series of MATLAB coded functions. The models predict the normalized radar cross section (NRCS), σ^o, for a given sea state based on the operating frequency, graze angle and polarization with some models also requiring wind

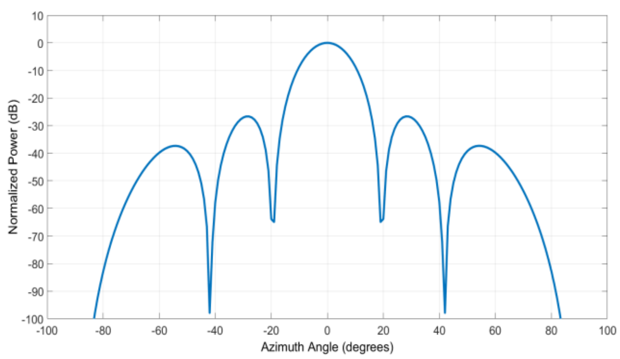

Figure 2. A 6-element two-way MIMO antenna pattern.

direction. The relationship between the NRCS and the radar clutter cross section, σ_c, is defined as follows [10]:

$$\sigma^o = \frac{\sigma_c}{A_f} \qquad (1)$$

where A_f is the effective area for a given beamwidth, B, viewing the ocean surface at a range, R, with a grazing angle, φ, defined as [10]:

$$A_f = \frac{\pi (BR)^2}{4 \sin \varphi} \qquad (2)$$

For the case of the simulated MIMO radar, it has a radiating beamwidth based on the the element pattern of the antenna, therefore σ_c will be properly accounted for during the simulation. The proposed method from [9] was used to calculate values of σ^o for all simulated ranges and angles. The results of the calculations for σ^o were then normally distributed to create a matrix of sea clutter RCS values. The sea clutter RCS positions are then uniformly distributed in height based on the sea state of the simulation. The simulation considers sea clutter as targets with an associated RCS and performs the same calculations as a normal target. For the scenario that will be discussed in the next section, sea clutter was introduced into every second sampled cell resulting in a total of 3840 sea clutter targets.

4. Performance Evaluation

To evaluate the performance of the developed software-testbed, three slow moving targets were placed in a 40° search sector abeam to a six-element uniform linear array (ULA) that is located 5 m above the ocean. The distances and angles to the targets are shown in Figure 3. The radar system is stationary while all three targets are travelling at speeds less than 20 knots (roughly 10 m/s) with RCS values ranging from 0.8 m^2 to 1.9 m^2. The targets are considered point scatters that fluctuate following a Sweling 1 model. A custom-built microstrip patch antenna was used for the transmitting and receiving elements with a gain of 8 dB. Figure 4 depicts the H-plane antenna pattern of the antenna. The scenario was run at an operating frequency of 8.8 GHz using time division Zadoff-Chu phase encoded pulses with a PRI of approximately 6.7 µs for an unambiguous range of less than 1 km. The compressed pulse range resolution

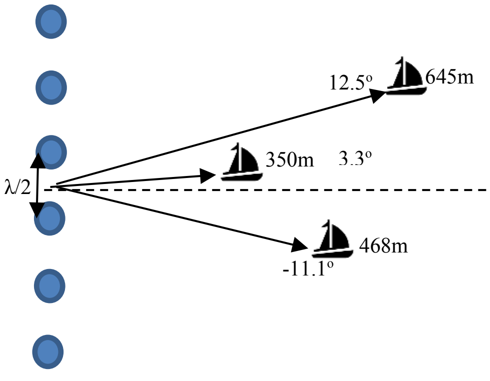

Figure 3. A depiction of the scenario used in the simulation where a 6 element ULA attempts to detect three targets.

size was set to 5 m. The transmitter output power was 100 W. Every transmit and receive element was used for this simulation resulting in the same two-way MIMO antenna pattern depicted in Figure 2. Sensitivity time control was used for all simulations to minimize clutter.

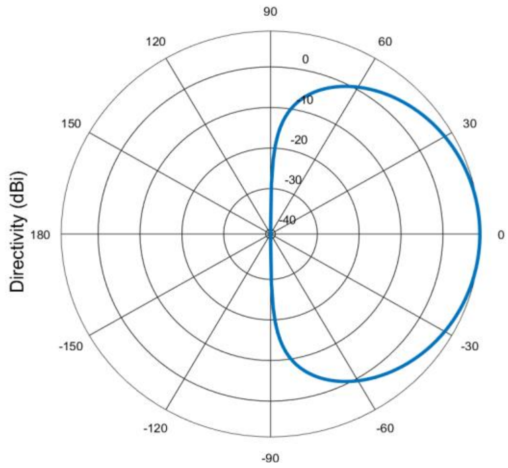

Figure 4. H-plane cut of the microstrip patch antenna used in the simulation.

The MIMO receiver was set to acquire a total of 36 returns before integration and subsequent beamforming could take place. This equates to a CPI of 241 µs allowing for each transmit and receive path to occur 6 times before processing begins. A CPI of 241 µs was the minimum required processing interval to match the SNR value of a single pulse from the phased array radar. The processor stores the 36 returns in memory and updates the radar picture every 6th pulse, dropping the oldest six returns. A refresh of six pulses was selected to allow a complete transmission cycle of all transmitters before refreshing the radar picture. For equal comparison, no integration was performed with the phased array radar simulation. The phased array performed a single transmission for every 1° of azimuth resulting in 40 transmissions to scan the entire search area. The total scan time for the phased array radar was 267 µs.

The first simulation was run for both radars without sea clutter to determine if the three targets were detectable against a cell-averaging CFAR detector. The results were similar for both radars. Figure 5 demonstrates the similarities between the two radars by depicting their returns for the target located at 350 m.

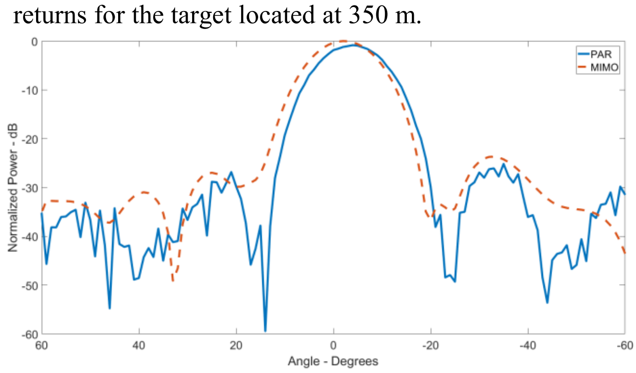

Figure 5. Comparison of radar returns of a target for a MIMO and phased array radar.

The radar return of the MIMO system of all three targets is depicted in a three-dimensional representation of the radar return against the CFAR threshold in Figure 6. The three targets exceeded the threshold detector and detection was maintained over multiple simulations. The MIMO radar simulation updated the radar picture every 6th echo return or every 40.2 µs whereas the phased array radar took 267 µs to update the same picture.

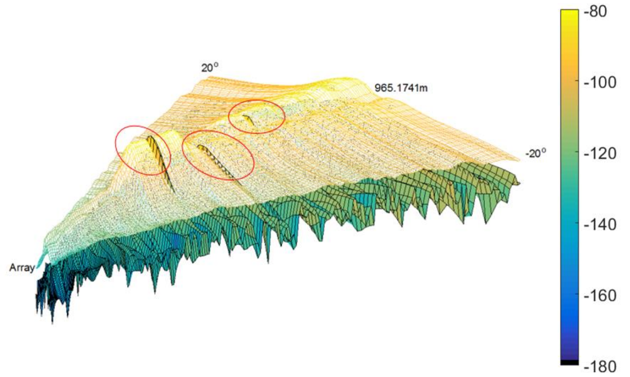

Figure 6. Detection of 3 targets with the simulated MIMO radar without sea clutter.

The subsequent test was run in the presence of sea state 3 clutter. The height of the sea clutter was uniformly distributed in height ranging from 0-1.25 m [11], for every sampled cell. All the settings from the previous simulation were applied again. Sea state 3 clutter raised the noise floor of the environment enough to shift the average threshold value of the CFAR detector by 20 dB; however, both radars were able to maintain detection of all three moving targets over multiple simulations. Figure 7 depicts the MIMO radar return of the three targets being detected above the threshold.

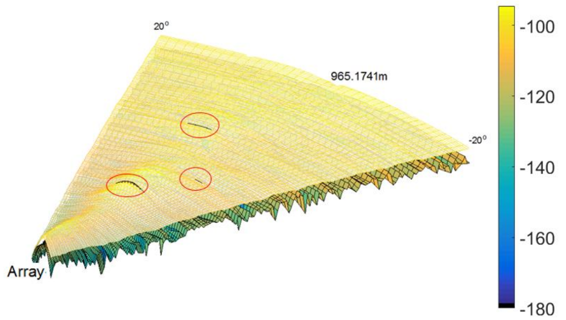

Figure 7. Detection of the same 3 targets with the MIMO radar, but with sea state 3 clutter.

5. Conclusion

The Simulink-based MIMO and phased array radar simulations provide an environment that allows for in-depth radar analysis and comparison. Preliminary results show that time division colocated MIMO radar is a suitable option for detecting multiple surface contacts in a cluttered sea environment. It was also demonstrated that for the given scenario, the MIMO radar provided a faster refresh rate of the radar picture compared to a phased array. Only one example was used for comparison of the two radar systems under a defined set of conditions. Future work includes a more in-depth statistical analysis of various scenarios using the simulation testbed in preparation for experimental work.

6. References

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