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IMPROVED DETECTION OF HYPERSONIC THREATS WITH RADAR USING IRREGULAR WAVEFORMS AND ADVANCED PROCESSING

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Abstract

Hypersonic weapons can pose a significant threat to the international security, as the characteristics in terms of speed, cruise altitude, and manoeuvrability differ significantly from other threats. This implies that the engagement timelines become extremely short and, hence, the detection, tracking, classification, and identification should be accomplished at large distances. To fulfil these tasks, current radar sensors will be pushed to or beyond their current limits. A potential solution to overcome certain limitations of modern radar systems is by using novel waveforms and advanced signal processing. Hence, the goal of this work is to demonstrate the potential of irregular waveforms and advanced processing for the detection of hypersonic threats. It is shown that their combination can significantly increase the detection performance and the measurement accuracy compared to multiple, medium pulse repetition frequency waveforms with linear signal processing.

Keywords

Advanced radar signal processing, Irregular waveforms, Hypersonic threats, Radar systems.

1. INTRODUCTION

The introduction of hypersonic weapons to the battlefield will be disruptive. High velocities, manoeuvrability, and relatively low cruising altitudes of these threats makes effective engagement difficult, as the first generation hypersonic missiles have unfortunately shown in the Ukraine [1]. The threat characteristics of the hypersonic weapons are significantly different than that of ballistic and cruise missiles and novel solutions are needed for successful interception [2], [3]. The complexity of the problem suggests that a sensor network could be an effective solution for a successful kill-chain.

That said, the required performance for the tasks assigned to each sensor within such a network might be pushed to or beyond the current limits. The engagement timelines become extremely short due to the hypersonic speed, cruise altitude, and threats' manoeuvrability requiring that the detection, tracking, classification, and identification are accomplished at large distances to have sufficient time for target engagement, where several tasks are primarily fulfilled by radar systems.

Detection by radar systems depends on the system parameters and on the radar cross section (RCS) of the target, where a small value implies that it is more difficulty to observe. Currently, there are several studies in e.g., EDA and NATO to understand the phenomenology of hypersonic threats [3], [4]. Plasma effects surrounding the hypersonic vehicle makes the to-be-expected RCS value highly uncertain and it is possibly subjected to significant variations.

Modern surveillance radar systems employ multiple, medium pulse repetition frequency (PRF) type of waveforms with linear signal processing on receive for the detection of typical current targets. The waveforms commonly consist of several bursts, each burst containing multiple identical pulses at a constant carrier frequency and PRF. To obtain unambiguous estimates of the target's range and velocity from the measurements, the concept of staggered PRF waveforms is often used. This concept results in longer transmission times and processing losses,

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but the signal processing is rather straightforward and suited for real-time implementation. For the surveillance of hypersonic threats, the staggered PRF waveforms and linear processing are pushed to their practical limits [5] in terms of detection performance and in terms of unambiguously estimating both the range and the radial velocity parameters of the target.

To summarize, the hypersonic threats pose challenges to individual radar systems in a network as: 1) the threat needs to be detected at a large range leading to a low signal-to-noise-ratio scenario; and 2) the staggered PRF waveforms with linear processing experience practical limitations leading to significant detection performance degradation.

Recent developments of commercial high performance computing using graphical processing units increases the processing capabilities far beyond the requirements of linear signal processing used in many radar systems. It potentially allows for the use of waveforms consisting of irregular intervals and/or irregular modulations combined with advanced, and possibly non-linear and iterative, signal processing techniques. This combination will [6], [7]: a) not experience ambiguities in the range and the radial velocity measurements, b) significantly decrease the processing losses currently experienced by linear processing, c) increase the accuracy of the range and velocity measurements, and d) decrease the susceptibility against deceptive electronic counter measures. Figure 1 provides an artist's impression of naval radar employing irregular waveforms and advanced processing using high performance computing. The potential of these novel concepts for radar is currently also explored within a DARPA program [8].

The goal of this work is to demonstrate the potential of irregular waveforms and advanced processing for the detection of hypersonic threats. In particular, it shows that the combination of irregular waveforms and advanced processing offers a potential solution for unambiguous range and velocity measurements while simultaneously increasing the detection range. In addition, this work also discusses our developments in 1) decreasing the computational load of the proposed advanced algorithms and 2) effective suppression of clutter when using irregular waveforms.

The paper is organized as follows. Irregular waveforms and advanced processing concepts for radar is given in Section 2. In Section 3, the performance of this solution for the hypersonic threat detection is given. The usage of irregular waveforms and advanced processing in the civil domain is briefly discussed in Section 4 followed by the conclusions in Section 5.

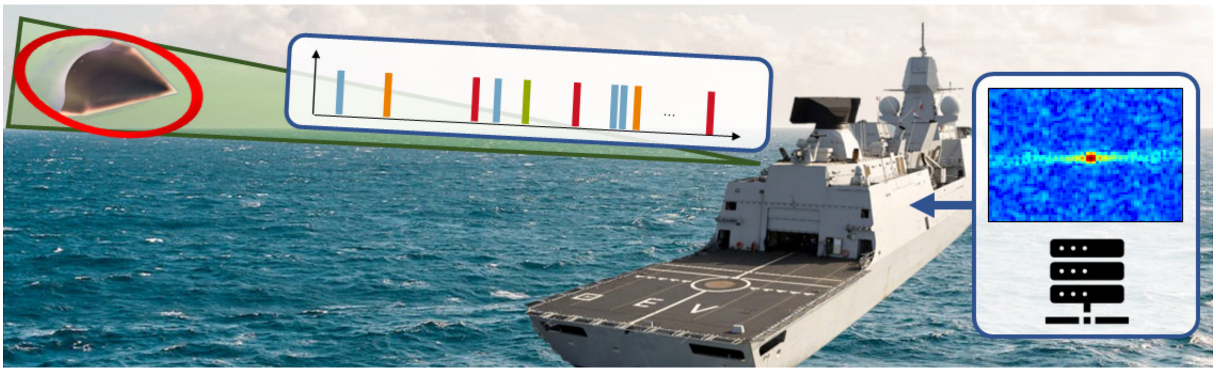

Figure 1. Artist's impression of naval radar employing irregular waveforms and advanced processing against hypersonic threats.

2. IRREGULAR PULSED WAVEFORMS AND ADVANCED PROCESSING

The emerging threat of hypersonic weapons imposes the need to expand the maximum detection range and the capabilities of unambiguously measuring the targets' ranges and velocities. To understand the limitations of systems employing staggered PRF waveforms with linear processing, we will discuss them briefly. Staggered PRF waveforms consist of a number of bursts where the i-th burst contains multiple identical pulses with a constant PRF_i and a constant carrier frequency f_i. The regularity in each burst leads to ambiguities in the range and the velocity measurements of the target. As the required range and velocity spans far exceed the requirements for surveillance of hypersonic threats, multiple bursts at different PRFs and carrier frequencies are transmitted and processed, with varying unambiguous ranges and velocities, see blue and orange areas in Figure 2.(left). A target appears for each burst at a different location, see blue crosses and orange plusses. Unfolding the measurements of each burst beyond this ambiguous domain and then overlaying the measurements of the different bursts will reveal the true location of the target, see green circle. In practice, the unfolding capabilities are limited [5], e.g., due to noise, blind ranges, and clutter filtering, which significantly decreases the detection performance.

Introducing irregularities in the pulse interval and/or pulse modulation is a way to resolve the range and the velocity ambiguities [7]. Absence of ambiguities removes the need for multiple incoherent bursts and the transmission time could be used for a single coherent waveform that significantly increases the detection performance[2]. On the other hand, processing irregular waveforms requires 1) advanced match filtering schemes to produce a high quality range and velocity image without significant losses and 2) the target detection requires iterative optimization techniques to handle the higher sidelobe levels of irregular waveforms. With increased sidelobes, strong targets can mask weak targets. For example, an airliner or sea clutter in the beam might mask a hypersonic target. To mitigate both issue, advanced processing plays a crucial role.

In this section, we highlight our recent developments [7], [9]-[14] in the design and processing of irregular waveforms, show how the extra degrees of freedom can be exploited, and how clutter can be supressed in an efficient way. In this section, we focus our discussion on irregular pulse intervals, but the techniques can also be extended to waveforms with irregular pulse modulation.

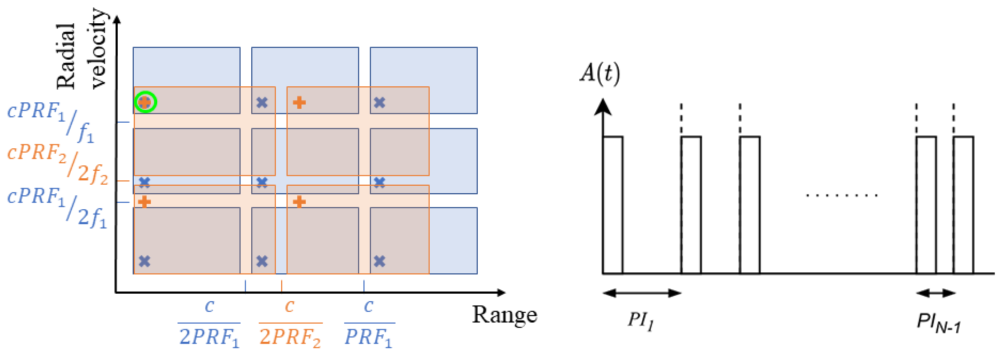

Figure 2. Illustration of the unfolding of a staggered waveform employing two bursts (left) and (right) an illustration of amplitude over time of an irregular pulse interval waveform.

2.1. WAVEFORM WITH IRREGULAR INTERVALS

To suppress periodic ambiguities in both range and velocity, irregularity can be introduced in the *pulse interval* (PI), e.g., by selecting the pulse interval of sequential transmitted pulses randomly on a uniform interval between a minimum and maximum value, see Figure 2.(right). In Figure 3, two ambiguity functions are shown for a) a *linear frequency modulated* (LFM) waveform with a regular PRF of 2 kHz at 1.2 GHz, and b) an LFM waveform with random PIs. Clearly, in Figure 3.(left), the range ambiguities at multiples of 75 km and the velocity ambiguities at multiples of 250 m/s are visible for the regular PRF waveform as peaks with almost equal amplitude to the main peak in the origin. The sidelobes, i.e., contributions in regions outside the main peak, are significantly lower for the regular PRF waveform compared to the irregular PI waveform, in both the range and radial velocity domain. However, removing the periodic ambiguities of the regular PRF waveform by using random PI waveforms come at the cost of increased sidelobes.

The ambiguity function represents the signal contribution of a single object at zero range and with zero radial

2 The detection performance will increase under the assumption that the target remains coherent during the coherent integration time.

velocity. A complex radar scene is a superposition of amplitude scaled ambiguity functions of all targets and clutter, where the peak at (0,0) is moved to the range and velocity of the targets and clutter. Detecting these peaks allows to find objects in the scene. However, the strong sidelobes of slow moving clutter nearby can mask a fast moving hypersonic far away.

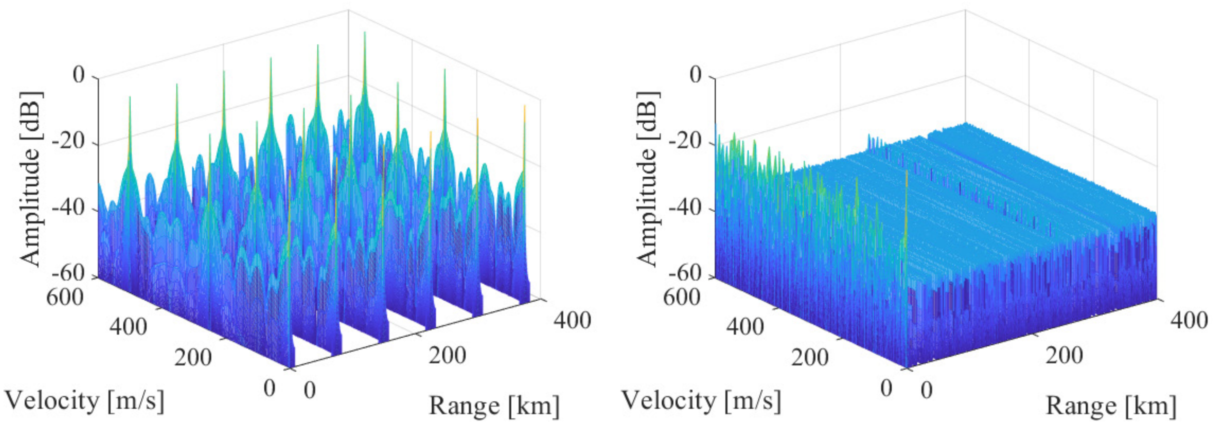

Figure 3. Ambiguity function of (left) a regular LFM waveform with PRF of 2 kHz at 1.2 GHz and (right) LFM waveform with random PIs on [0.25, 0.75] ms interval.

The sidelobes of the waveform can be modified and lowered in particular regions by optimizing the PI for particular scenarios. For example, lowering sidelobes of a clutter in the range-velocity region where the hypersonic target should be initially detected. See [9]-[11] for our current developments in waveform optimization.

2.3. CLUTTER SUPPRESSION

The detection of hypersonic threats at a large distance by radar systems close to the earth's surface implies small grazing angles, i.e., observations close to the horizon. This will introduce strong surface clutter into the observation. However, efficient mitigation of clutter for irregular waveforms is an open topic in the literature.

To mitigate the clutter in the received signal for irregular waveforms, we propose a modified filtering approach. Similar to standard *moving target indication* (MTI), our irregular MTI method exploits the fact that most clutter is found at close range and has a small velocity component [12]. When the irregular waveform has pulses with equivalent modulation, a simple and computationally efficient clutter filter can be implemented, see [12] for the details. The effectiveness of our irregular MTI method is highlighted in the next section.

The irregular MTI clutter filter is inadequate for filtering of waveforms with irregular modulation. We recently introduced a clutter filtering technique at a slight increased computational cost [13] to handle waveforms with both irregular pulse intervals and irregular modulation.

2.4. TARGET ESTIMATION WITH IRREGULAR WAVEFORMS

Irregular waveforms require advanced processing to 1) avoid large matched filtering losses due to the Doppler sensitivity of the waveform and 2) to handle the high sidelobe levels.

To generate an image of the scene similar to Figure 3 used for target detection, matched filtering (MF) is applied. Linear processing usually employs a *one dimensional* (1D) range MF and a separate 1D Doppler filter bank under the assumption that range and velocity processing can be performed independently. However, for irregular waveforms, independent processing leads to significant MF losses. To mitigate the matched filtering losses, in this paper, a *two dimensional* (2D) MF is applied, where a 2D MF accounts for all velocity shifts of interest for each pulse delay [14]. However, the 2D MF significantly increases the computational load compared to independent linear 1D processing.

Recently, we proposed an approximate 2D MF based on subpulse processing [12] that reduces the computational overhead and that can be efficiently computed by hardware accelerated FFTs.

To mitigate the high sidelobe levels of irregular waveforms, iterative processing techniques can be applied. As the radar only detects a couple of objects in the scene, the solution to our detection problem is sparse and, therefore, sparse optimization is applied in this paper. Many solvers exist to solve a sparse optimization problem, e.g., see [15], in our example the non-linear, iterative *orthogonal matching pursuit* (OMP) [14] is applied in Section 3.

3. SIMULATION STUDY OF THE HYPERSONIC THREAT DETECTION

In this section, the performance of the proposed irregular waveform and advanced, iterative 2D signal processing is compared to that of a typical staggered, medium PRF waveform with linear 1D processing for the detection of a hypersonic threat.

3.1. HYPERSONIC SURVEILLANCE SCENARIO DESCRIPTION

We consider the case of a single hypersonic threat modelled with a Swerling case I fluctuation model. The radial velocity can range between Mach 2 and Mach 18 and the threat is placed at a range between 300 km and 700 km from the radar system. The simulation includes sea surface clutter with sea state 3 modelled by the NRL model [16]. The clutter horizon is 12 km and the velocity spectrum is taken as Gaussian with 0.72 m/s standard deviation. For the sea clutter generation, it is assumed that the radar beam is fixed at an elevation of 3°. The target range and velocity are uniformly drawn from the above given brackets and only one target is present in every Monte Carlo run. For every simulation of the 3000 Monte Carlo runs, a new realization of the thermal noise, of the clutter, and of the target is generated on which the staggered PRF waveform with 1D processing and the irregular PI waveform with 2D processing are evaluated.

The staggered medium-PRF waveform consists of four bursts where the carrier frequency, number of pulses, and PRF are changed per burst. The pairs are chosen (1.23 GHz, 13, 1600 Hz), (1.20 GHz, 15, 1800 Hz), (1.18 GHz, 17, 2000 Hz), (1.21 GHz, 19, 2300 Hz), respectively. All pulses have an LFM modulation with a pulse length of 50 μs. For processing, a three-pulse MTI filter is used to mitigate clutter, a Hamming window for pulse compression is applied and for Doppler filtering a Hanning window is used. For the detector, the individual bursts are processed with the cell-averaging constant false alarm detector and the individual burst detections are then combined using an 2-out-of-4 detector.

The irregular waveform consists of irregular PIs with equal modulation for each pulse within the burst. The waveform is composed of 64 pulses with an LFM modulation, a pulse duration of 50 μs at 1.2 GHz centre frequency. Each PI is chosen randomly between [0.25, 0.75] ms and the initial phase of each pulse is chosen randomly. For processing of the irregular waveform, the irregular MTI clutter filtering is applied and the detection is performed by OMP combined with 2D matched filtering. Note that both waveforms have equal energy on target, i.e., equal number of pulses and pulse length, and they have both a dwell time of 32 ms.

The detection threshold is chosen for a probability of false alarms of 10-8. To account for migration artifacts, a detection is considered to be correct when the range and radial velocity are estimated within ±150 m and ±75 m/s, respectively, of the true target range and radial velocity.

3.2. SIMULATION RESULTS

The simulation results are presented and discussed in this subsection. The percentage of detected targets for the staggered medium-PRF waveform with linear processing is 11.8% compared to 73.5% for the irregular PI waveform with 2D matched filtering for 3000 Monte Carlo runs. The detection performance of the staggered medium-PRF waveform with linear processing is significantly less than the irregular PI waveforms with advanced processing. The performance degradation is partially caused by the three-pulse MTI clutter filter. Yet, a significant part of the performance degradation is due to the practical limitations of the staggered medium-PRF waveform with linear processing [5]. This part of the performance degradation may be solved by increasing transmit power, i.e., deploying a larger-sized system, however, the irregular waveforms with advanced processing may also offer a solution.

Figure 4 and Figure 5 show the detection histograms in range and velocity, respectively, for the staggered medium-PRF waveform and irregular PI waveform. The significant increase in detected targets can be noted even at large ranges. The detection histogram for the velocity is non-uniform for the staggered medium-PRF waveform, due to the practical limitations of linear processing. For the irregular waveforms with advanced processing, the detection histogram for velocity is uniform, as the 2D matched filter compensates for the velocity of the target.

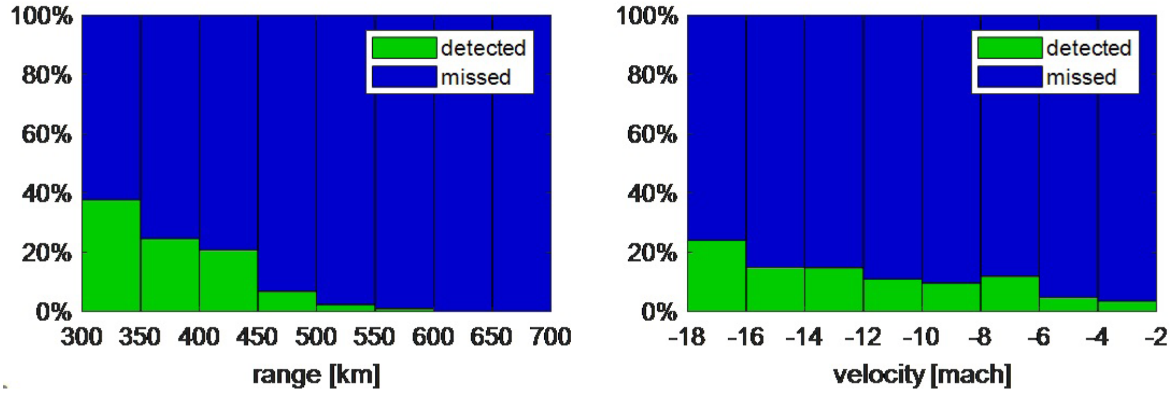

Figure 4. The detection histograms in range with (left) the staggered medium-PRF waveform with linear processing and (right) irregular PI waveform with advanced processing.

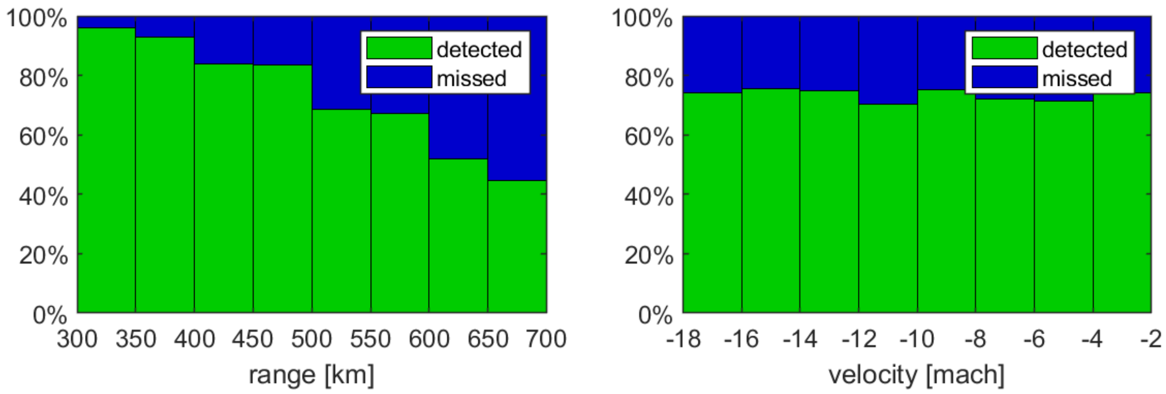

Figure 5. The detection histograms in velocity with (left) the staggered medium-PRF waveform with linear processing and (right) irregular PI waveform with advanced processing.

The bias of the range and velocity estimates of the target using the staggered medium-PRF waveform with linear processing are 8.56 m and -0.14 m/s, respectively, compared to -1.42 m and 0.02 m/s for the irregular waveform with advanced processing. The standard deviation of the estimates are 14.21 m and 7.08 m/s for the staggered medium-PRF waveform and 2.32 m and 1.10 m/s for irregular waveform. Clearly, our proposed irregular waveform and advanced processing improves the accuracy of the estimates roughly by a factor 6. Improved accuracy of the estimates improves radar tracker initialization and it increases the track accuracy.

The irregular waveforms and advanced processing significantly improves the detection range that can also be traded-off for shorter transmission times and/or usage of less transmit power. The shorter transmission time means that the freed radar time budget can be used for other tasks, e.g., more simultaneous active tracks. Decreasing the transmission power would allow for smaller-sized systems or improved energy/covertness profile of the sensor.

4. IRREGULAR WAVEFORMS AND ADVANCED PROCESSING IN THE CIVIL DOMAIN

The strength of irregular waveforms, or non-uniform sampling, combined with advanced processing has not gone unnoticed in the civil domain. In particular, advanced processing for imaging in medical and acoustic sensors and in radioastronomy have been matured and deployed in products. Within the medical imaging field, the usage of advanced processing significantly reduces the acquisition time, i.e., patient in the machine, while simultaneously sharpening the image. For example, Philips, General Electric and Siemens exploit it for MRI, CT, PET, and X-rays scanners [17], [18], [19]. Another field that highly benefits of sharpened images using advanced processing is in the acoustic domain. In particular, the oil and gas industry uses, e.g., seismic imaging, to geologically map the Earth's crust for natural resources [20]. Within radioastronomy, example of advanced processing for sharpened imaging and calibration can be found in the LOFAR and SKA telescopes [21], [22].

5. CONCLUSIONS

This paper has demonstrated the potential of waveforms consisting of irregular pulse intervals combined with advanced processing for the detection of hypersonic threats. In particular, we have shown that the novel waveforms and associated iterative 2D processing offer a potential solution to overcome the practical limitations of staggered PRF waveforms and linear 1D processing. Particularly for the hypersonic threat detection, this novel combination can significantly increase the detection performance in terms of the detection range and the accuracy of the estimated range and velocity measurements of the target. It has also been shown that the irregular MTI clutter filtering technique can sufficiently suppress the simulated sea clutter to be able to detect the hypersonic threats at large distances. Hence, the presented approach has the potential to significantly improve the detection range of the radar system and, simultaneously, it improves the track quality that can be constructed from these measurements. These advantages can contribute to early warning detection and increased time to engage hypersonic threats using radar systems.

Current efforts are focussed on thoroughly analysing the impact the usage of irregular waveforms and advanced signal processing within the complete radar processing chain and to improve robustness of these methods. In addition, the focus is on efficient implementations tailored to (specific) processing platforms in terms of computational load and memory capabilities. Moreover, designing waveforms in dynamic environments particularly for the hypersonic threats is an ongoing research topic.

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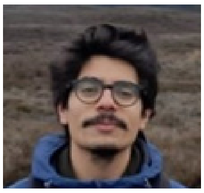

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