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RESEARCH ARTICLE

Pulsed Active Sonar Using Generalized Sinusoidal Frequency Modulation for High-Speed Underwater Target Detection and Tracking

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ABSTRACT For decades, the soft-kill strategy which detects high-speed underwater targets with passive sonar and attract the targets using decoys has been used. However, recently, the paradigm to respond to the high-speed underwater targets is shifting to a hard-kill method that directly intercepts the targets. Therefore, an active sonar detection and tracking technique is required to estimate the exact location of the target. Existing detection and tracking techniques using active sonar divide pulses either temporally or along the frequency axis, transmitting pulses in various directions within a pulse repetition interval. This division, however, leads to a reduction in the time-bandwidth product, consequently diminishing detection performance. Therefore, this paper proposes a generalized sinusoidal frequency modulation (GSFM)-based pulsed active sonar (PAS). The proposed PAS-GSFM employs short pulses for a quick update of target estimates, but the orthogonality between pulses of GSFM allows pulses to maximize bandwidth, thus high detection performance can be expected. Two types of simulations were performed to verify the performance of the proposed PAS-GSFM. First, the performance comparison with PAS-linear frequency modulation (LFM), and second, the comparison between the proposed method and continuous active sonar (CAS)-GSFM. Through the evaluation, the superiority of the proposed method over PAS-LFM and competitiveness compared to CAS-GSFM were proved.

INDEX TERMS High-speed underwater target, GSFM, pulsed active sonar, target detection and tracking.

I. INTRODUCTION

Sonar systems play a pivotal role in various fields such as marine exploration, naval defense, and commercial fisheries, serving as the eyes beneath the water. They are indispensable devices for acquiring data about moving targets in underwater environments and are critical for tasks ranging from detecting potential threats in naval operations to identifying fish schools in commercial ventures. Based on their operating principles, these systems can be broadly divided into passive and active sonar [1], [2], [3], [4], [5], [6].

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The increasing proficiency of underwater vehicles in noise reduction has rendered traditional passive sonar methods inadequate, necessitating the development of more responsive active sonar technologies. This is particularly critical for scenarios involving high-speed underwater targets where delayed detection could lead to irreversible consequences. In particular, the rapid update of target position information is crucial to avoid collisions with fast-moving underwater objects, such as torpedoes [7], [8].

Active sonar systems are largely classified into pulsed active sonar (PAS) and continuous active sonar (CAS) based on their pulse transmission methods. The PAS dedicates most of the processing time to receive an echo signal by transmitting a single pulse within a pulse repetition interval

(PRI). Conversely, CAS benefits from a high target revisit rate (TRR) by continuously transmitting a pulse train consisting of multiple subpulses. Although continuous active sonar (CAS) systems offer some advantages, they are compromised by the direct blast (DBL) issue, where the strength of the transmitted pulse can overwhelm the receiver, leading to a loss of crucial target information [9], [10], [11]. Although mitigation techniques such as null steering exist [12], [13], even with DBL power reduction, its energy often surpasses the echo signal.

Among the fundamental transmission techniques of PAS, one is the PRI-based technique [14]. In general, omni-directional sonar systems, which transmit signals in all directions with even power, are commonly used. However, after the first contact, directional transmission can be particularly used to track the highly probable target located near in order to increase directivity index (DI) and signal to noise ratio. In these directional systems, the PRI-based technique entails transmitting a single pulse per cycle to search for targets in a specified direction. Since only one direction can be detected per cycle, it necessitates an extended time period to identify targets within a large area. This inherent limitation in detection speed can be hazardous, particularly in scenarios where rapid response is critical, such as avoiding potential collisions with high-speed underwater objects. The limitations of PRI-based techniques become particularly evident in situations where speed is of the essence, such as in naval defense operations against rapidly approaching threats, where they fail to provide the timely and reliable target detection that is so vitally needed.

To address this, divided pulse length-based and multi-frequency-based transmission techniques have been suggested [15]. Firstly, the divided pulse length-based transmission technique enables pulse transmission with temporal variations within one cycle, allowing detection in multiple directions. However, accurate target detection becomes problematic when reverberation and echo signals are received from multiple directions between pulse transmission angles. Subsequently, the multi-frequency-based transmission technique splits the available frequency bands and transmits pulses simultaneously in various directions. Each transmission direction possesses a separated bandwidth, reducing correlation between subpulses from adjacent directions compared to the divided pulse length-based technique, thus facilitating relatively accurate target detection. However, bandwidth division may lead to a time-bandwidth product (TBP) loss, diminishing detection performance.

On the other hand, efforts to develop novel pulse type superior to conventional continuous wave (CW) and linear frequency modulation (LFM), i.e., Comb [16], Costas [17], generalized sinusoidal frequency modulation (GSFM) [18], have been conducted. Among those, GSFM can generate several types of orthogonal pulses even when their bandwidths overlap entirely. This property represents a significant departure from conventional approaches. GSFM can be designed in numerous forms depending on its parameters, and at specific parameter values, it exhibits similar characteristics to sinusoidal frequency modulation (SFM) or LFM [19].

Several studies have employed the characteristics of GSFM to design CAS systems [19], [20], [21]. While theoretical analyses assured orthogonality without dividing frequency band of subpulses, experiments revealed that when the frequency bands fully overlapped, the impact of DBL becomes pronounced. Consequently, the adoption of an overlapping band pulse train (OBPT) proved more effective for target detection [19]. Additionally, researchers pursued the optimization of GSFM parameters, namely ρ and α to design pulse trains specifically for optimal target detection and tracking [21]. Our research builds on these foundational studies, showcasing how GSFM not only enhances CAS system performance but also how our novel PAS-GSFM approach significantly outstrips traditional methods, offering rapid target detection and tracking with reduced pulse lengths without sacrificing the time-bandwidth product.

As countermeasures for high-speed underwater targets, the soft-kill strategy which uses decoys to deceive approaching targets has been operated. However, recently, paradigm to respond the high-speed underwater targets is changing to hard-kill strategy which aims to directly intercept and destroy the threat. Thus, an active sonar detection and tracking technique is required to estimate the exact location of the target. Conventional detection and tracking techniques using active sonar divided pulses in time or frequency axis to transmit pulses in various directions in a PRI. However, this results in a decrease in TBP and eventually reduces detection performance. Thus, we propose PAS using GSFM for the high-speed underwater target detection and tracking in this paper. The orthogonal property of GSFM pulses makes TBP maintained even when pulse length is reduced to achieve fast update of targets. In order to verify our proposed PAS-GSFM, two types of simulation are performed. First, target detection performance of the proposed method is compared with that of PAS using LFM with a simple scenario. Second, the tracking performance of the proposed method is compared with that of CAS using GSFM in the environment that simulates to detect and track near targets approaching rapidly.

In this paper, we present the structured organization as follows. Section II introduces the PAS and CAS system along with the characteristics of GSFM waveform. In Section III, a novel PAS-based system with GSFM is proposed, specifically designed for rapid target tracking. Subsequently, in Section IV, we conduct underwater simulations to analyze both the conventional CAS system and the proposed PAS-based system, considering CW, LFM, GSFM, and various tracking algorithms. Finally, in Section V, we conclude our study with a comprehensive discussion of the findings.

II. RELATED WORKS

A. GENERALIZED SINUSOIDAL FREQUENCY MODULATION

GSFM is a pulse waveform proposed by Hague in [18], designed to address the limitation of the high sidelobes observed in the conventional SFM. The equation representing GSFM is given by:

$$\varphi_{GSFM}(t) = \frac{\beta}{t^{\rho-1}} \sin(\frac{2\pi\alpha t^{\rho}}{\rho}) \quad (1)$$
$$\beta = \frac{BW}{2\alpha} \quad (2)$$
$$C = \alpha T^{\alpha} \quad (3)$$

here, α denotes the frequency modulation parameter, BW represents the bandwidth, β is the modulation index, and T represents the length of a subpulse. Additionally, ρ is a parameter determining the shape of the pulse, with a value equal to or greater than 1. If ρ equals 1, the shape of GSFM becomes identical to the conventional SFM. As can be observed in Figure 1, as ρ increases, GSFM demonstrates increased asymmetry in the time-frequency axis. Furthermore, C indicates the number of cycles in the instantaneous frequency function of GSFM, and as equation (3) suggests, it is determined by α. A distinctive feature of GSFM is its spike-like shape in the time-Doppler plane, characterized by pronounced mainlobes and diminished sidelobes. It is possible to generate orthogonal subpulses using a simple time/frequency reflection (TFR) technique with GSFM. The TFR method involves inverting signals in the time and frequency axes, and it includes the following types: forward-time (FT), FT/flipped-frequency (FT/FF), reverse-time (RT), RT/FF, time-symmetric (TS), and TS/FF. Among them, all but TS and TS/FF guarantee distinct orthogonality [20].

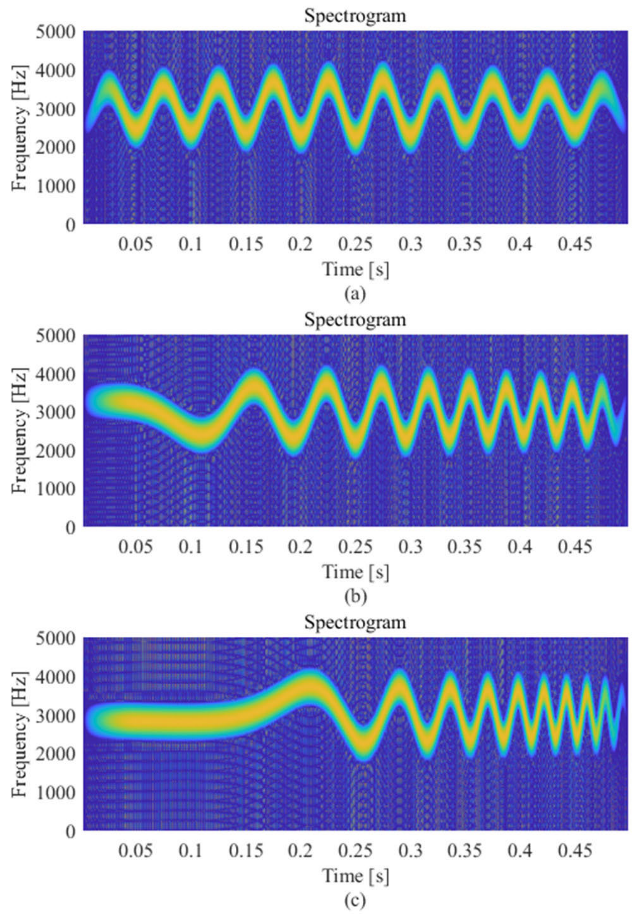

FIGURE 1. Spectrograms of a GSFM pulses with a pulse duration of 0.5s (a) $\rho = 1$, C=10, (b) $\rho = 2$, C=10, (c) $\rho = 3.5$, C=10. As ρ increases, the asymmetry of the pulses becomes more pronounced. Notably, when ρ is 1, the shape of the GSFM pulse becomes identical to that of the conventional SFM.

B. CONTINUOUS ACTIVE SONAR

Figure 2 illustrates the signal transmission methods of conventional PAS and CAS. Depending on the number of subpulses used within one cycle, CAS has a TRR that is more than N times higher compared to PAS. The basic signal models for PAS and CAS are as follows:

$$s_{PAS}(t) = e^{j\varphi(t)}e^{j2\pi f_c t} \quad (4)$$
$$s_{CAS}(t) = \sum_{n=1}^{N} s_n(t-(n-1)T) \quad (5)$$
$$s_n(t) = e^{j\varphi_n(t)}e^{j2\pi f_c t}, \quad (6)$$

where t represents the time index, $\varphi(t)$ is the phase modulation function, f_c denotes the carrier center frequency, N is the number of subpulses, and n indicates the index of subpulses. For PAS, as there is only one pulse in a cycle, the size of the matched filter is fixed. However, for CAS, the size of the matched filter can be adjusted based on an appropriate filter size where coherence is maintained. When the transmission period for CAS and PAS is the same, the TRR can be set higher in CAS, depending on the conditions set for the subpulses. On the other hand, PAS, after transmitting a pulse once in the transmission cycle, only receives for the remainder of the time, meaning its TRR must inevitably be the same as the pulse transmission period.

Conventional CAS systems, which typically employed CW or LFM, necessitated the separation of frequency bands for their subpulses. These CAS configurations have a notably high duty cycle. Transitioning to the GSFM-based approach, one would replace the subpulses in the previously defined equations (4) and (5) with those of GSFM in (1). It is essential that the parameters of the GSFM subpulses be optimized to ensure their orthogonality.

Contrary to expectations, when the frequency bands of CAS were made to overlap perfectly, target detection became challenging due to DBL problem [21]. However, when the pulses were designed in the form of OBPT where only portions of the frequency bands overlapped, the system could capitalize on the clear peak of ambiguity function of GSFM while reducing the influence of DBL.

CAS systems should be operated in bistatic or multistatic configurations where transmitter and receiver are separated, whereas PAS systems can be operated all kind of sonar condition including monostatic sonar. In addition, CAS systems can obtain high TRR but it suffers DBL problem and

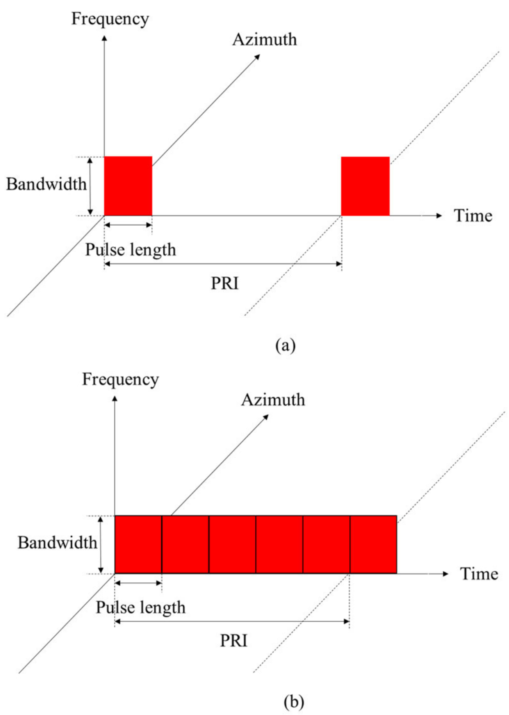

FIGURE 2. Pulse transmission technique concept diagram: (a) pulsed active sonar, (b) continuous active sonar. In the conventional PAS, a single signal is transmitted for each pulse period, while CAS transmits a continuous signal.

overloading on the transmitter and receiver due to the high duty cycle.

III. PROPOSED METHOD

In general, omnidirectional transmission is used for active sonar. However, the case considered in this paper is that directional transmission for high directivity index and signal to noise ratio is used to search and track toward the highly probable area where the near target is located after the first contact. In this case, N subpulses are transmitted to search N directions in a PRI. Basically, N subpulses are sequentially composed and transmitted in time domain. However, accurate target detection is hard to achieve due to reduced TBP and lack of orthogonality between subpulses. Subsequently, N subpulses divided in frequency domain can be used for searching and tracking N direction simultaneously. With this method, orthogonality between subpulses are guaranteed, but TBP reduction due to band division is inevitable.

To solve the problem of the conventional methods, we propose a pulse transmission method based on GSFM. The conceptual description of the proposed approach is provided in Figure 3. Orthogonal GSFM subpulses are sequentially transmitted to the interested search area. As depicted in Figure 4, our proposed method involves transmitting GSFM pulses with completely overlapping frequency bands simultaneously in multiple directions. This ensures a superior TBP in comparison to traditional PAS transmission methods.

To design the orthogonal subpulses, the ambiguity function (AF) is a pivotal concept, representing the matched filtering result based on each time delay and Doppler factor. This function can vary depending on the pulse used for matched filtering, allowing us to categorize it into auto AF and cross AF. The detailed equation of auto AF and cross AF are as follows [19]:

$$\chi_{auto}(\tau, \eta) = \sqrt{\eta} \int_{-\infty}^{\infty} s_n(t) s_n^*(\eta(t-\tau))dt \tag{7}$$

$$\chi_{cross}(\tau, \eta) = \sqrt{\eta} \int_{-\infty}^{\infty} s_n(t) s_m^*(\eta(t-\tau))dt, \tag{8}$$

where τ is time-delay, η represents Doppler scaling factor, and both n and m signify the indices of distinct subpulses. Furthermore, the peak cross-correlation level (PCCL) is another vital metric, signifying the highest peak value observed in the cross AF. The mathematical representation for PCCL is provided as follows:

$$PCCL_{n,m} = \max \left| \chi_{n,m} \right|. \tag{9}$$

Using these definitions, unlike previous studies that utilized GSFM [18], [19], [20], [21], we have substantially reduced pulse length and minimized the pulse period, which leads to a high TRR. As a result, unlike the traditional PAS, our proposed method becomes capable of tracking high-speed underwater vehicles.

Initially, to align with our concept requirements, we design suitable GSFM subpulses. To achieve this, our approach generates subpulses in an N by D dimension by randomly setting pulse parameters such as ρ, cycle C, and TFR. This ensures orthogonality between subpulses even at shorter signal pulse lengths. Following this, a greedy algorithm is used to ascertain that the peak values from matched filtering between each subpulse does not surpass a predetermined threshold. Here, N denotes the number of subpulses per direction to prevent range ambiguity along the time axis, and D represents the number of detection directions. Since we aim to transmit in five directions with five subpulses each, we utilize a total of 25 subpulses. The parameter search range for the GSFM is defined as shown in Table 1, which was based on the findings from Kim's study [21]. Among the 25 subpulses, the peak cross-correlation level of 10 subpulses has been provided as a sample. As can be discerned from the Figure 5, even when the frequency bands overlap, the correlation between the GSFM subpulses remains low, ensuring orthogonality.

IV. EXPERIMENTS

A. EXPERIMENTAL SETUP

In this study, we established a simulated underwater environment to validate the feasibility of the proposed method. To present superior detection performance of the proposed PAS-GSFM to PAS-LFM, we designed an experiment with a

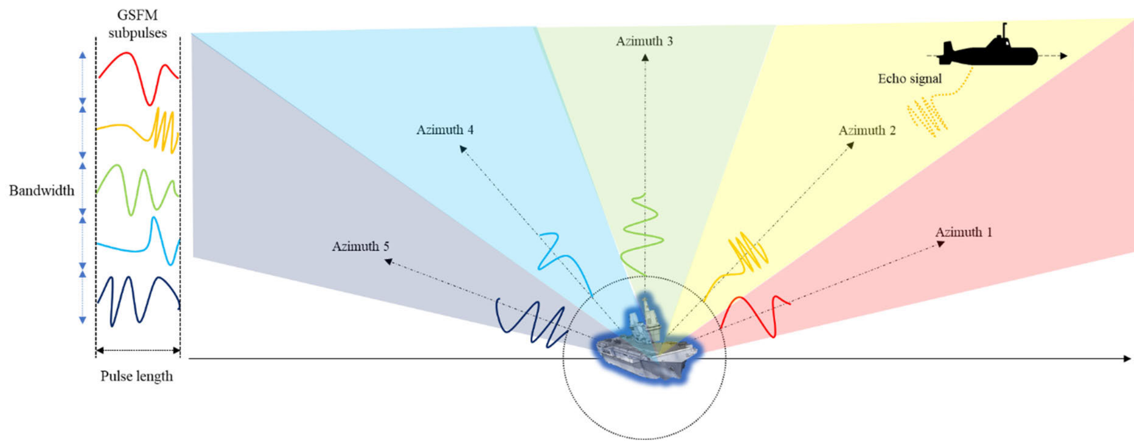

FIGURE 3. Conceptual diagram of the proposed signal transmission method. Signals are transmitted in nearly simultaneous fashion in five directions relative to the transmitter. The bandwidth and pulse length of signals transmitted in each direction are set to be identical. To maximize the TBP, the available frequency range is fully utilized while maintaining orthogonality between the signals using GSFM. A straightforward optimization process of GSFM parameters is conducted.

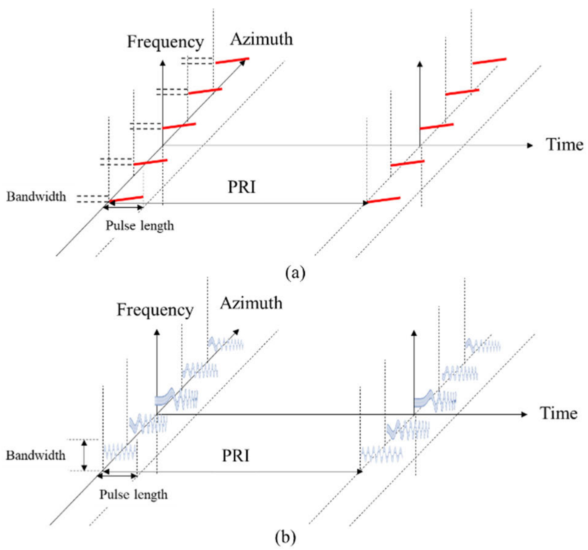

FIGURE 4. Illustration of the PAS-based signal transmission: (a) shows the case of LFM, where frequency bands are separated, (b) illustrates the proposed method using GSFM without any separation of frequency bands. Compared to LFM, GSFM allows for a greater TBP as it does not divide the frequency bands, effectively increasing the TBP by a factor equal to the number of subpulses.

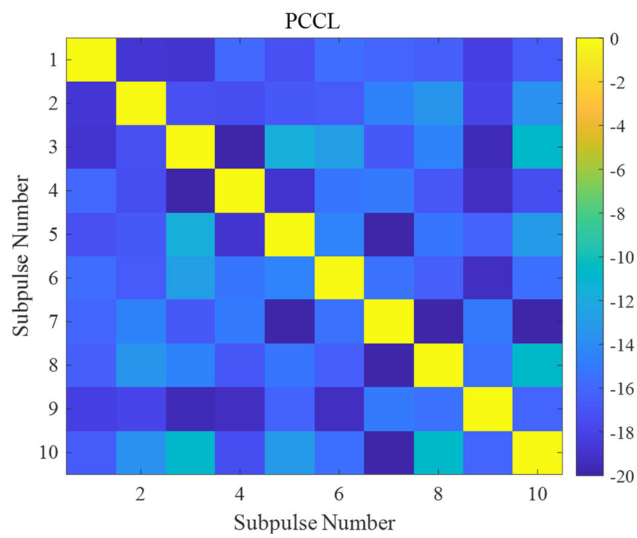

FIGURE 5. PCCL between GSFM subpulses. The parameters of each GSFM subpulse were determined using the greedy algorithm, and were designed to ensure that the PCCL does not exceed -12dB.

TABLE 1. Search range for GSFM subpulses. To maintain orthogonality between subpulses, random combinations of the parameters within this range were explored using a greedy algorithm.

	Range
ρ	[1:0.01:3.5]
C	[1:1:40]
TFR	[FT, FT/FF, RT, RT/FF, TS, TS/FF]

simple scenario. In this experiment, detection bearings were set at five different angles: −20, −10, 0, 10, and 20 degree, each with an assumed beam width of approximately 10 degrees. To simulate a real underwater environment, a reverberation model [22] was applied, along with the addition of white noise at a signal-to-noise ratio of −5 dB. We executed a scenario where a target moves for 10 s in the simulated underwater environment. Figure 6 represents overall arrangement and the target trajectory.

Subsequently, the experimental setup was configured based on the reference [21] to compare and analyze the performance with the CAS-based system. For CAS, a pulse train consisting of 8 subpulses, each with a length of 0.5 s, was constructed. In this scenario, by shifting each pulse and conducting matched filtering, location of the target can be updated every 0.5 s. To achieve an equivalent TRR in the proposed PAS environment, we set the pulse length to 0.05 s and the pulse transmission interval to 0.5 s.

TABLE 2. Parameters for pulse types in CAS and the proposed method for simulation. Contrary to the proposed method, the frequency band of GSFM used in CAS was divided.

	CAS			PAS		
	CW	LFM	GSFM	CW	LFM	GSFM (proposed)
Center frequency	[2,550 Hz:125 Hz:3,450 Hz]			[2,400 Hz:200 Hz:3,400 Hz]		3,000 Hz
Bandwidth of subpulses	-	125Hz		-	200Hz	1,000 Hz
Number of subpulses	8			5		5

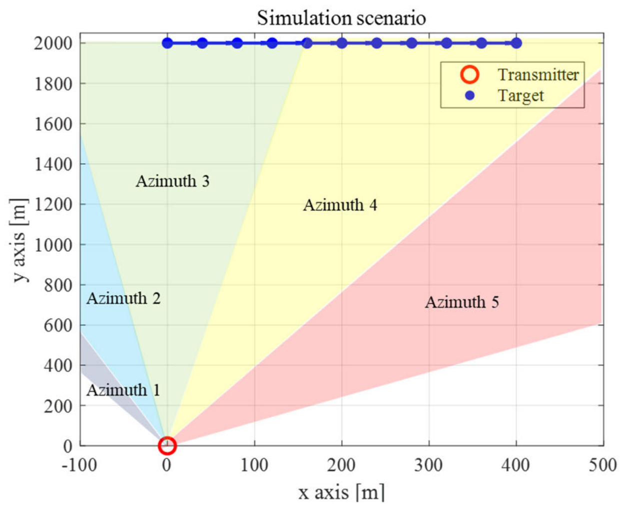

FIGURE 6. Simulation 1 scenario: Starting from an initial position of [0, 2000 m], the target advances at a speed of [40 m/s, 0]. The moving direction of the targets is marked with blue arrows to clearly indicate the trajectory. The corresponding search areas for each transmission azimuth are also indicated.

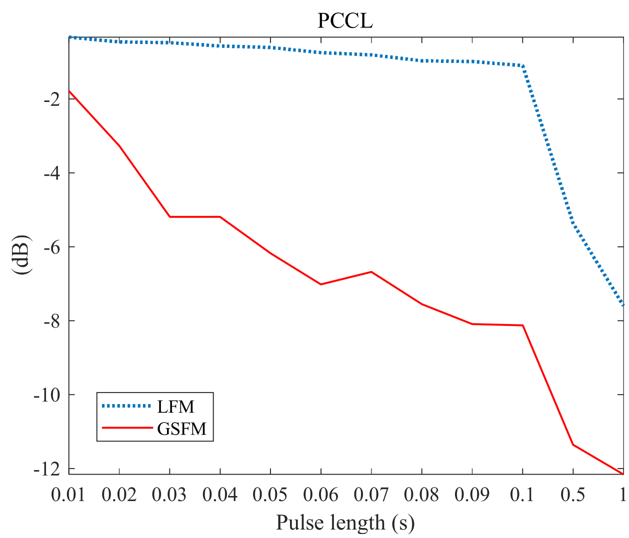

FIGURE 7. Maximum value of matched filtering of subpulses according to pulse length (dotted line: LFM, solid line: GSFM). This graph illustrates the trend with respect to pulse length, but the pulses shown are not the ones used in the actual simulation.

To verify the viability of using a 0.05 s pulse length, we computed the average PCCL between frequency-separated LFM and entirely overlapping GSFM subpulses at this duration. The pulse conditions utilized are delineated in Table 2. As Figure 7 illustrates, compared to the traditional LFM, GSFM more readily maintained orthogonality. This indicates that even with a shorter pulse length of 0.05 s, GSFM can ensure sufficient orthogonality.

In our proposed approach, a total of 5 subpulses were introduced in the time-domain to prevent distance estimation ambiguity. Contrary to CAS, in our approach using GSFM, the frequency band was not divided. To account for the echo environment, we employed the point scattering model [23]. The base SRR was set to -13dB, and synthetic white noise of 3dB was added. This configuration was based on the study that incorporated GSFM into CAS [21].

The speed of the high-speed underwater target is set to 40 knots since the speed of targets was set to 20 m/s in the simulation for torpedo alarming [22]. This speed is set to encompass both the speed of nuclear-powered submarines and the high-velocity torpedoes they can launch [24], [25].

In our research, a scenario was designed to compare and analyze the target tracking performance of various signal transmission systems. The scenario, depicted in Figure 8, involves an underwater vehicle moving at approximately 40 knots ($\approx$20 m/s), approaching the transmitter and receiver from an initial distance of 4000 m. In this scenario, the total duration is 150 s. Vertical positions of the transmitter, receiver, and the target are not considered. Velocity v of the target was set to vary randomly over time to mimic real-world conditions.

In addition, to validate the capability of our proposed PAS-GSFM system for tracking high-speed underwater entities similarly to the CAS-based system, we employed a suite of established Kalman filter-based tracking algorithms, including the extended Kalman filter (EKF) and the unscented Kalman filter (UKF) [21], [26], [27], [28], [29]. EKF is known for its effectiveness in tracking targets with nonlinear motion, whereas UKF is valued for its ability

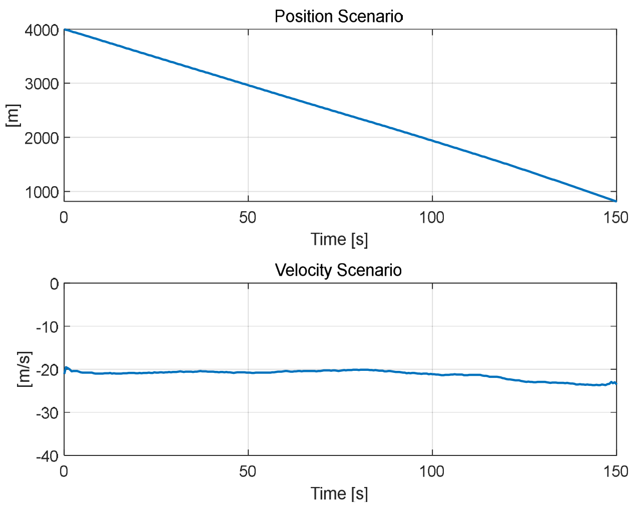

FIGURE 8. **Target movement scenarios: initial speed of 20 m/s and initial distance of 4,000m. This speed fall within the range of typical velocities for nuclear submarines or torpedoes [24], [25].**

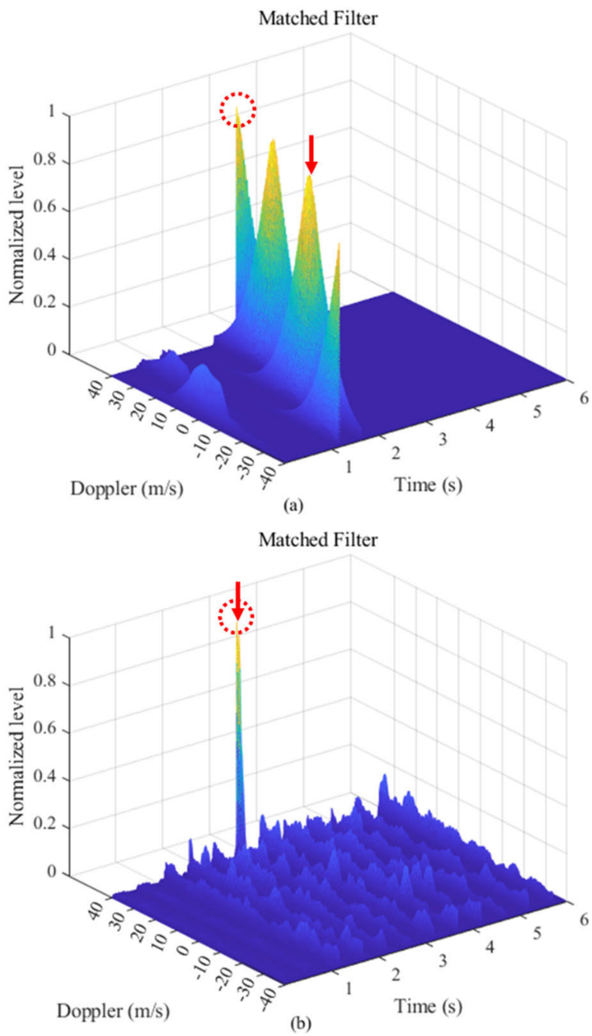

FIGURE 9. **Results of matched Filtering in a PAS-based system: (a) LFM, (b) GSFM. Dotted circles indicate the actual target position, while solid arrows point to the observed peaks.**

to handle high-dimensional state spaces and more complex nonlinearities. It should be noted that the primary objective is not to establish superiority in performance metrics, but to demonstrate that our PAS-GSFM approach can track high-speed underwater targets comparably to CAS systems. Each filtering method has its distinct merits, tailored to cope with varying situations and dynamics.

B. EXPERIMENTAL RESULTS

For evaluation, two types of simulations were performed to verify the performance of the proposed PAS-GSFM: the simulation to prove superior detection performance over PAS-LFM and the target tracking performance comparison between the proposed method and CAS-GSFM, respectively.

First, we conducted an experiment to compare LFM and GSFM within the PAS framework. The results of this preliminary comparison can be seen in Figure 9 and 10. Figure 9 shows that the Doppler-time matched filtering for LFM has a peak in a location other than the actual target, leading to distance estimation errors. On the other hand, matched filtering results of GSFM display a significant orthogonality between subpulses, causing other peaks to be much lower compared to the peak at location of the actual target. Figure 10 further illustrates that LFM results in considerable errors in distance and velocity estimations, even when SRR is high, whereas GSFM performs substantially better, with errors staying within 1 m and 1 m/s for distance and velocity, respectively, when the SRR is above −10 dB. However, both systems experience higher errors when the SRR drops to −15 dB due to the impact of reverberation on matched filtering. Furthermore, Figure 11 provides a summary of the approximate azimuth estimation results under PAS scenario. The higher orthogonality between subpulses transmitted in different directions by GSFM leads to less confusion in azimuth estimation compared to the results with LFM.

After our initial tests showed the benefits of using GSFM in a PAS system, we moved on to more detailed experiments to fully check our proposed PAS-based approach. In these experiments, we looked at different ways to send pulses, different pulse shapes, tracking methods, and SRRs. We measured performance using the root mean square error (RMSE) between the real and estimated locations and speeds. Averaged over 1,000 trials done with the Monte Carlo method.

Figure 12 presents the results when using the basic KF under the most challenging SRR condition of this study, set at −13 dB. In this simulation, the performance of our proposed PAS-based approach was found to be superior to that of the conventional CAS system, even at this low SRR level. This enhanced performance is attributed to two main factors. First, the PAS system does not suffer the DBL problem which is

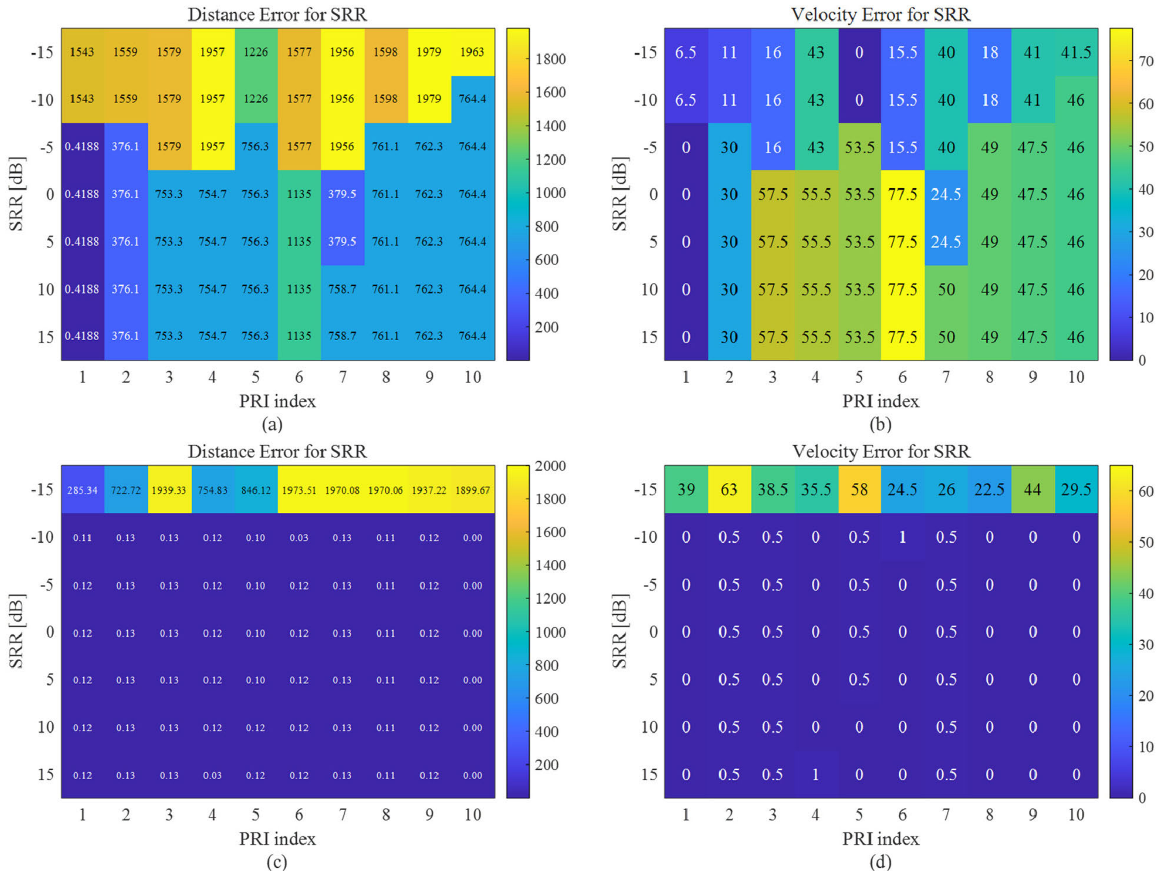

FIGURE 10. Errors in target estimations across various SRR Values (-15 dB to 15 dB): (a) distance Error in LFM, (b) velocity error in LFM, (c) distance Error in GSFM, (d) velocity Error in GSFM. Note that with the use of GSFM, distance of the target and velocity can be accurately estimated except in poor SRR conditions (SRR = −15dB), whereas LFM tends to yield less accurate estimations due to the confusion with adjacent frequency band pulses.

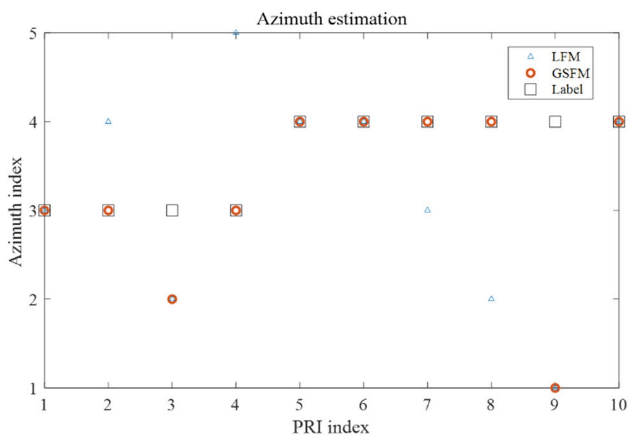

FIGURE 11. Azimuth estimation for an SRR = −10 dB. This figure shows the computed target direction in the situation depicted in Figure 6. (triangle: LFM, circle: GSFM, square: true target location within the simulated setting).

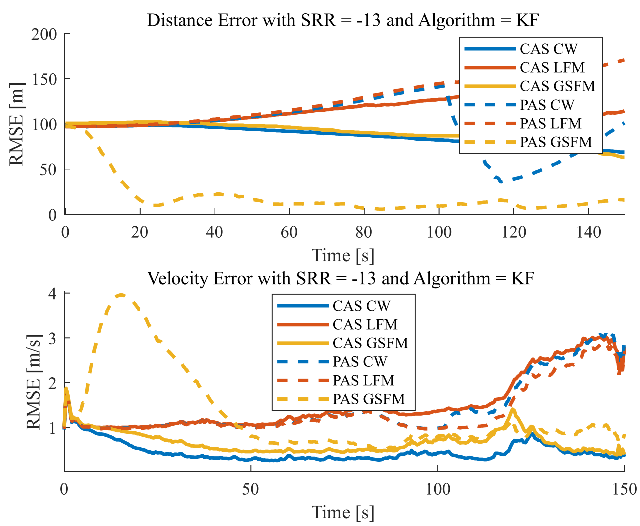

FIGURE 12. Sample results from high-speed target tracking experiments for scenario. Kalman filter-based distance and velocity estimation for CW, LFM, and GSFM. (SRR = −13 dB).

major problem of the CAS system. Second, our proposed PAS-GSFM takes advantage of directional transmission, which leads to a stronger reception of the target signal under the same conditions. Notably, for the PAS-CW, an abrupt fluctuation in the error can be observed, and this is primarily due to the significant range measurement uncertainty inherent to CW signals. Considering the representative design of hull-mounted sonar in [10] and active sonar equations, we assigned a 5 dB additional gain for directional transmission over omnidirectional transmission and a 6 dB penalty for band division of LFM. Furthermore, these results validate our decision to employ GSFM within the PAS framework. The suboptimal performance of LFM, which tends to have a reduced TBP compared to GSFM, actually emphasizes the effectiveness of our proposed concept.

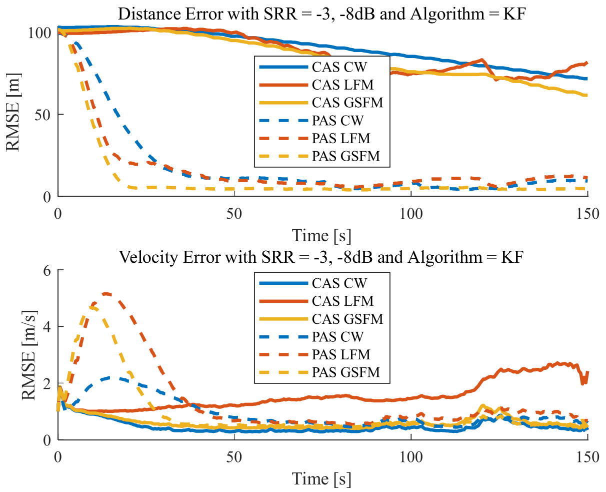

FIGURE 13. Sample results from target tracking experiments for scenario. Distance estimation results for CW, LFM, and GSFM using KF. (Average results for SRR cases of −3 dB and −8 dB).

Subsequently, we performed additional tests at higher SRR conditions of −8 dB and −3 dB. In Figure 13, we detail the comparative results of distance and velocity estimations achieved by employing KF on our PAS-GSFM system versus the CAS under SRR conditions of −8 dB and −3 dB. These specific SRR values were selected to represent moderate and mildly challenging noise environments, respectively, providing a comprehensive view of system performance across varying levels of acoustic clutter. The distance estimations were derived using a predefined target trajectory, assuming constant speed and bearing typical of torpedo-like underwater objects. Velocity estimations were computed considering the Doppler shift observed due to target movement. Although the proposed method did not show overwhelmingly superior target tracking results compared to conventional systems, it should be emphasized that the primary goal of our research was not a quantitative performance comparison against other systems. This shows that our proposed concept works effectively in simulation, successfully tracking the distance and velocity of high-speed underwater targets.

Figure 14 extends our analysis to include advanced tracking algorithms, namely EKF and UKF, in addition to the basic KF. These algorithms were chosen for their proven effectiveness in handling nonlinear system dynamics, which are representative of complex underwater vehicle movements. The experiments were designed to simulate a linear trajectory for the target, a common scenario in anti-submarine warfare. The EKF and UKF algorithms were tested for

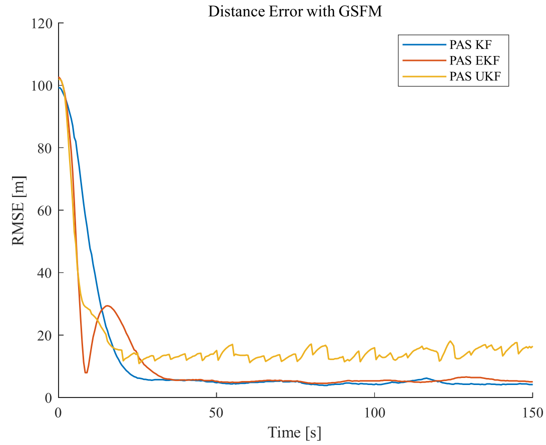

FIGURE 14. Sample results from target tracking experiments for scenario 1. Distance estimation results for GSFM using KF, EKF, and UKF. (Average results for SRR cases of −3 dB and −8 dB).

their precision in tracking rapidly maneuvering underwater vehicles, reflecting real-world operational conditions where targets may exhibit erratic movements. Despite the primary linear nature of our scenario, these filters provided nuanced insights into the tracking capabilities of our PAS-GSFM system. The comparative results show that while the basic KF performed well due to the scenario's simplicity, the EKF and UKF demonstrated potential for superior performance in more complex situations, highlighting the adaptability of our proposed system. In real-world conditions where the target's movement patterns diversify, there is potential to adopt the EKF or UKF over the basic KF.

C. DISCUSSION

In [10], long CW is suggested for transmitting active sonar signals to detect torpedoes. This is mainly from the fact that doppler filtering is effective due to the high doppler ($\Delta f \approx$ 80 Hz when $v = 20$ m/s and $f_c = 3$ kHz), which makes the performance evaluation in noise-limited environments where pulse length and source level (SL) are important. In this case, performance of reverberation rejection is further improved by applying pulse shaping (or weighted CW) and shading which further lowers sidelobe levels in frequency and space [30]. However, long CW results in low range resolution and large blind zone in general, and in the case that sufficiently high doppler does not occur due to reduced velocity of the target, doppler filtering is not effective and the performance should be assessed in the reverberation-limited environments where the narrow band CW is vulnerable [30].

On the one hand, LFM is a wideband transmitting signal. Since the signal is doppler insensitive and exists in the broad bandwidth, reverberation is a dominant factor for the performance of LFM. In the reverberation-limited environment, active sonar equation is denoted as in [10],

$$10 \log R = 10 \log(B/\theta_h) - S_b - 41 + TS - 5 \log d + 5 \log n \quad (10)$$

where R is the detection range in km, B is the bandwidth, θ_h is the horizontal 3dB beamwidth, S_b is the backscattering strength of the bottom, TS is the target strength, d is a parameter related with detection threshold, n is the number of successive time samples used by the operator (or automatic system) in making the decision. According to the equation (10), the performance of the wideband transmitting signal in the reverberation-limited area is dependent to the bandwidth and 3dB beamwidth. When applying directional transmission, the equation (10) expressed as follows:

$$20\log R = 10\log(B/(\theta_h \cdot \theta_v)) - S_v - 23 + TS - 5\log d + 5\log n \quad (11)$$

where θ_v is the vertical 3dB beamwidth, S_v is the volume scattering strength of the layer. Considering the representative hull-mounted sonar (HMS) design in [10], torpedo detection range is approximately 60 m when LFM is omnidirectionally transmitted in horizontal direction. The low range is primarily originated from the much lower TS compared to submarines, which makes hard to detect the small high-speed moving object. In addition, when applying directional transmission with LFM, the transmission signal bandwidth is divided by the number of azimuths of the interested area. Thus, the expected performance improvement of the advantage of the directional transmission is reduced.

On the other hand, GSFM is the generalized version of SFM which has superior performance in reverberation suppression (RS). Contrary to expectations, however, the RS performance of GSFM is not that outstanding. In [31], the RS of GSFM was analyzed by the Q-function derived by integrating ambiguity function with respect to time axis, the typical RS performance measure. The analysis presented that slight increases of ρ from one (which means SFM) results in the flat Q-function similar with that of LFM. Nevertheless, thanks to the orthogonality of the family of GSFM pulses, we can obtain the reasonable detection range utilizing the directional transmission with large enough bandwidth and narrow beamwidths. In the above HMS setting, if the bandwidth is modified to 2 kHz and θ_h and θ_v are 6 and 10 degrees, respectively, and the simultaneous detection azimuths are set to 5, the detection ranges of PAS-LFM and PAS-GSFM are about 515 m and about 1.15 km, respectively, which the PAS-GSFM is about twice as high as the PAS-LFM.

Finally, performance analysis in the reverberation environment of the CAS is on-going research area [31]. In general, there is a trade-off between the coherent processing interval (CPI) of the matched filter and the target acceleration tolerance. Long CPI in order to increase TBP leads to the target acceleration intolerance. In addition, CAS is the inherently bistatic sonar, and thus is influenced by DBL. To reduce the effect of DBL, null steering beamforming is generally applied to the direction of DBL. In [31], the DBL is notched by about -60 dB using null steering beamforming, however if the transmitter and receiver are closely located and the SL is high, the DBL is not sufficiently reduced, resulting in target echo masking.

V. CONCLUSION

In this paper, we proposed a novel PAS-GSFM pulse transmission technique to tackle the limitations of traditional PAS and CAS-based systems for detecting and tracking the high-speed underwater target. The standard PAS system suffers from a low duty cycle, leading to a significantly low TRR, making it unsuitable for tracking high-speed underwater targets. In contrast, while the CAS system can detect such targets, it is substantially affected by the DBL. To resolve this problem, we introduced a concept that utilizes PAS while reducing the pulse length to boost the TRR. By utilizing the orthogonal property between GSFM subpulses, we aimed to reduce TBP losses associated with short pulse durations. Furthermore, through the PAS-based directional transmission concept, we anticipate an increase in the SRR, thereby enhancing both target detection probability and tracking performance. To validate the proposed method, we set up scenario considering underwater vehicles moving at 40 knots. The proposed method was compared and analyzed across different pulse transmission systems, pulse types, tracking algorithms, and SRR settings. Our experimental findings revealed that the proposed method consistently outperformed the traditional CAS across all SRR conditions.

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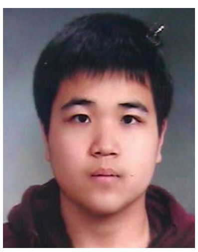

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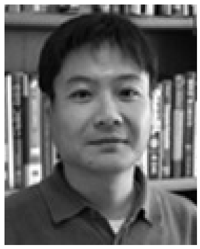

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