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14. ABSTRACT Our objectives are 1) to consider multistatic continuous active sonar (MCAS) systems, aka high duty cycle systems, that involve the transmission and reception of multiple continuous probing sequences or long duty cycle sequences, 2) to investigate the merits of MCAS on its ability to achieve significantly enhanced target detection and parameter estimation performance through exploiting the advantages of continuous illumination and spatial diversity, 3) to develop innovative techniques to synthesize spectrally contained continuous sequence sets with low correlation sidelobe levels for the MCAS transmission, so that the so-generated sequences meet the spectral containment restrictions and the weak correlations among the received echoes can be exploited to improve the target detection performance, and 4) to apply robust, computationally efficient, and data-adaptive receiver signal processing algorithms to effectively mitigate the mutual interferences among multiple transmitters and suppress direct blasts for MCAS systems.				
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Enhanced Multistatic Active Sonar via Innovative Signal Processing

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LONG-TERM GOALS

Our goal is to address fundamental signal processing research issues for enhanced multistatic active sonar systems. To effectively mitigate the reverberation problems and direct blasts encountered in shallow water, both probing waveform synthesis and adaptive receive filter design techniques should be investigated. To efficiently and accurately estimate the target positions and velocities, both target association schemes and weighted target parameter estimation methods should be devised.

OBJECTIVES

Our objectives of the current effort are 1) to consider multistatic continuous active sonar (MCAS) systems, also referred to as high duty cycle systems, that involve the transmission and reception of multiple continuous probing sequences or long duty cycle sequences, 2) to investigate the merits of MCAS on its ability to achieve significantly enhanced target detection and parameter estimation performance through exploiting the advantages of continuous illumination and spatial diversity, 3) to develop innovative techniques to synthesize spectrally contained continuous sequence sets with low correlation sidelobe levels for the MCAS transmission, so that the so-generated sequences meet the spectral containment restrictions and the weak correlations among the received echoes can be exploited to improve the target detection performance, and 4) to apply robust, computationally efficient, and data-adaptive receiver signal processing algorithms to effectively mitigate the mutual interferences among multiple transmitters and suppress direct blasts for MCAS systems.

APPROACH

The transmitted sequence set plays a critical role in an MCAS system since the performance of the system is determined by the accuracy with which the interpretation of the received signal matches the true target information in the region of interrogation. A well-designed waveform set, which possesses good auto- and cross-correlation properties, provides low correlation sidelobe levels so that the correlations among different echoes and the same echo with different time delays are minimized to improve the target detection performance. Moreover, the oceanic environment and the hardware system require that the so-generated sequences should satisfy spectrum containment restrictions. We consider modifying our recently proposed Periodic Cyclic Algorithm-New (PeCAN) method, which focuses only on the correlation performance of the sequence set but does not take into account spectrum containment restrictions.

We also consider novel receiver design techniques to improve the overall performance of the MCAS system and to compensate for the deficiencies in waveform synthesis.

The key individuals participating in this work include the PI, Dr. Jian Li, her Ph.D. students, Mr. Kexin Zhao and Mr. Shujian Yu, her postdoctoral associate Dr. Junli Liang, her visiting scientist, Dr. Johan Karlsson, and her visiting professor, Dr. Petre Stoica, all of the University of Florida.

WORK COMPLETED

We have devised a new algorithm to design spectrally-contained continuous periodic sequence sets for MCAS systems. Specifically, the proposed method synthesizes the sequence set utilizing the fast Fourier transform (FFT) computations and adopts flexible modulus constraints. Thus it can be also used for aperiodic sequence set design for the MCAS systems as well as pulsed sequence set for the pulsed active sonar (PAS) systems.

In addition to the well-known MCAS advantage that the transmission of continuous sequences can effectively alleviate the negative impact of the man-made noise on marine life, we have discovered that compared to its pulsed counterpart, the continuous probing waveforms can have wider passbands under the same spectrum containment restriction. This translates into higher range resolutions for MCAS systems. Moreover, we can achieve significantly enhanced performance of target detection and parameter estimation through exploiting continuous illumination and spatial diversity.

For MCAS systems, we have also considered novel receiver design techniques to improve the overall performance of the active sonar system and to compensate for the deficiencies in waveform synthesis. We have considered two adaptive receiver designs, namely the iterative adaptive approach (IAA) and the sparse learning via iterative minimization (SLIM) method. Both approaches outperform the classical data-independent matched filter (MF) significantly. We have also considered a hybrid method that first uses IAA to compute a dense range-Doppler image, which is then, upon convergence, followed by a single step of SLIM. Since SLIM achieves sparsity based on solving a hierarchical Bayesian model through maximizing *a posteriori* probability density function, this single step of SLIM is referred to as a MAP step, and the resulting algorithm as the IAA-MAP algorithm. SLIM provides sparse results but is relatively sensitive to noise and disturbances. IAA tends to be more robust against noise and disturbances than SLIM. Due to the accurate and robust IAA result and a single step of SLIM, IAA-MAP is robust, sparse and accurate. The merits of IAA-MAP are desirable for achieving improved range-Doppler imaging and target parameter estimation.

RESULTS

Consider an MCAS system equipped with 2 transmitters and 4 receivers. The system geometry is illustrated in Figure 1. The coordinate vectors of the four receivers Rx1, Rx2, Rx3, and Rx4 are $r_1 = [-500, 1000]$, $r_2 = [1000, -500]$, $r_3 = [2500, 1000]$, and $r_4 = [1000, 2500]$, respectively (the unit of distance is meter). Two transmitters, Tx1 and Tx2, are located at $t_1 = [0, 0]$ and $t_2 = [2000, 2000]$, respectively. A target, located at $[1150, 935]$, is moving in the field of view at a velocity of $v = [-1.8/\sqrt{2}, -1.8/\sqrt{2}]$ knots. In this simulation, we assume that during the time interval of interest $t \in [4.75s, 7.775s]$, the amplitudes of the reverberations follow an exponential distribution. The target reflection and direct blast (DB) coefficients and the variance (VA) of the zero-mean additive white

Gaussian noise at Rx1, Rx2, Rx3, or Rx4 are listed in Table I and the system parameters are summarized in Table II. Although the pulsed sequence has the same energy as its continuous counterparts, the former has higher instantaneous power level than the latter. In our simulations, the continuous sequences are unimodular while the magnitude of their pulsed counterpart is $\sqrt{3}$.

We consider first generating the spectrally-contained periodic continuous waveform (CW) for the aforementioned MCAS system. In this design, the cut-off frequency of the stopband is set as 300 Hz, i.e., $[-4000, -300]$ Hz and $[300, 4000]$ Hz are stopbands, and only the band $[-300, 300]$ Hz is available for transmission by the MCAS system. For comparison purposes, we also generate the pulsed sequence with the same parameters except for the shorter time duration. We generate Doppler-sensitive sequences with the desired magnitude spectrum over passband being equal to one. To satisfy the spectral containment restrictions over stopbands, the spectrum width of the passband cannot be larger than 200 Hz. To assess the performance of two so-designed sequences obtained with two independent random phase initializations, we compute their spectrum, auto-correlation function (ACF), and cross-correlation function (CCF), as shown in Figures 2(a), 2(b), and 2(c), respectively. To further analyze the ACF peak sidelobe level (PSL) and 3dB mainlobe width, the zoomed-in ACF is given in Figure 2(d). The results for the pulsed counterpart are shown in Figure 3. From Figures 2 and 3, it can be observed that the 90 Hz-passband width of the pulsed sequences is significantly narrower than that of the continuous ones in order to strictly satisfy the spectrum containment restrictions over stopbands. Additionally, the ACF mainlobe width of the pulsed sequences is about twice as large as the continuous ones and hence they have significantly poorer range resolution, compared to the latter.

Consider now the effect of employing different transmitting sequences (periodic CW and pulsed sequences) on the range-Doppler imaging performance. The receiver outputs are obtained via IAA-MAP and for comparison purposes the results obtained via the matched filter (MF) are also provided. The intensity of all range-Doppler images is normalized so that the peak is at 0 dB and is clipped below at -20 dB. Figures 4(a) and 4(b) show the imaging results for the periodic CW using MF (for the 2nd Tx-1st Rx pair) and IAA-MAP (for the 2nd Tx-1st Rx pair), respectively. Note that the locations of the direct blasts and main reverberations in the range-Doppler images are predictable since their Doppler scaling factors are equal to 1. Hence we can detect the moving target by finding the peaks corresponding to the target echoes after removing the row of pixels with unit Doppler scaling factor in the formed range-Doppler images, as shown in Figure 4(c). Additionally, the corresponding imaging results for the pulsed sequences are shown in the second row of Figure 4, respectively. By comparing Figures 4(a) and 4(d) with Figures 4(b) and 4(e), we can see that IAA-MAP possesses excellent interference suppression capabilities and produces much sharper images than MF. In addition, the comparison between Figures 4(b) and 4(f) suggests that the CAS systems can offer much higher Doppler resolution than the pulsed one.

IMPACT/APPLICATIONS

The littoral submarines are small, quiet, and non-nuclear, making active sonar an essential technology needed for their detection. Enhancing the multistatic active sonar network's capability through innovative waveform synthesis and receive filter design is critical to improving the Navy's ability to conduct anti-submarine warfare.

The spectrally-contained unimodular probing waveform sets we synthesize are hard to guess by the foe since the phase of each sample of the probing sequence is anywhere between 0 and 2π . This facilitates

covert sensing. Moreover, the Doppler sensitive nature of each probing waveform obviates the need to transmit two separate sequences, with one to achieve good range resolution and another to yield good Doppler resolution. Using the Doppler sensitive probing waveforms, we can achieve both good range resolution and good Doppler resolution simultaneously.

By using data-adaptive receive filters to process the received signals, the sidelobe problems of Doppler sensitive probing waveforms can be mitigated. Indeed, the range-Doppler images formed by using the adaptive receivers we devise possess low sidelobe level and high resolution properties. By using the efficient target association scheme and effective target parameter estimation method, the positions and velocities of the targets in the field of interest can be accurately estimated.

In a multistatic active sonar system that employs multiple transmitters and multiple receivers, we have shown that reliable adaptive receiver filters, via enhancing resolution and reducing sidelobe levels of the so-obtained range-Doppler images, significantly enhance the target detection ability and that refining the target position and velocity estimates using weighting provides significantly improved parameter estimation performance.

Finally, we have provided insights into the merits of continuous active sonar (CAS) systems over its pulsed counterparts. In the conventional pulsed active sonar (PAS) system, a powerful short pulse is transmitted, followed by a long listening time. This strategy has several shortcomings. Firstly, long listening time is needed to detect an object at a long distance, especially because the propagation speed of sound under water is rather low, as compared, for example, to the speed of light. As a consequence, a potential target is illuminated only during a short period of time, dictated by the pulse width, and the operator needs to wait for a complete cycle for a new detection opportunity to occur. Secondly, the high power waveforms emitted from the transmitters could induce environmental problems. Specifically, such underwater noise pollution could disrupt marine life and possibly even result in mass suicide of marine mammals. Thirdly, the Doppler resolution is inversely proportional to the pulse width and hence is low. In contrast, CAS systems provide several attractive advantages: i) CAS systems involve the transmission and reception of multiple continuous probing sequences and can achieve significantly enhanced performance of target detection and parameter estimation through exploitation of continuous illumination and spatial diversity; ii) the same amount of energy can be transmitted at a much lower peak power level compared to their pulsed counterpart, which alleviates the noise pollution to marine life; iii) the CAS Doppler resolution is inversely proportional to the coherent processing interval (CPI) and can be much higher than its pulsed counterpart, and iv) the CAS waveforms can have wider passbands under the same spectrum containment restriction than their PAS counterparts, resulting in higher range resolutions for CAS systems.

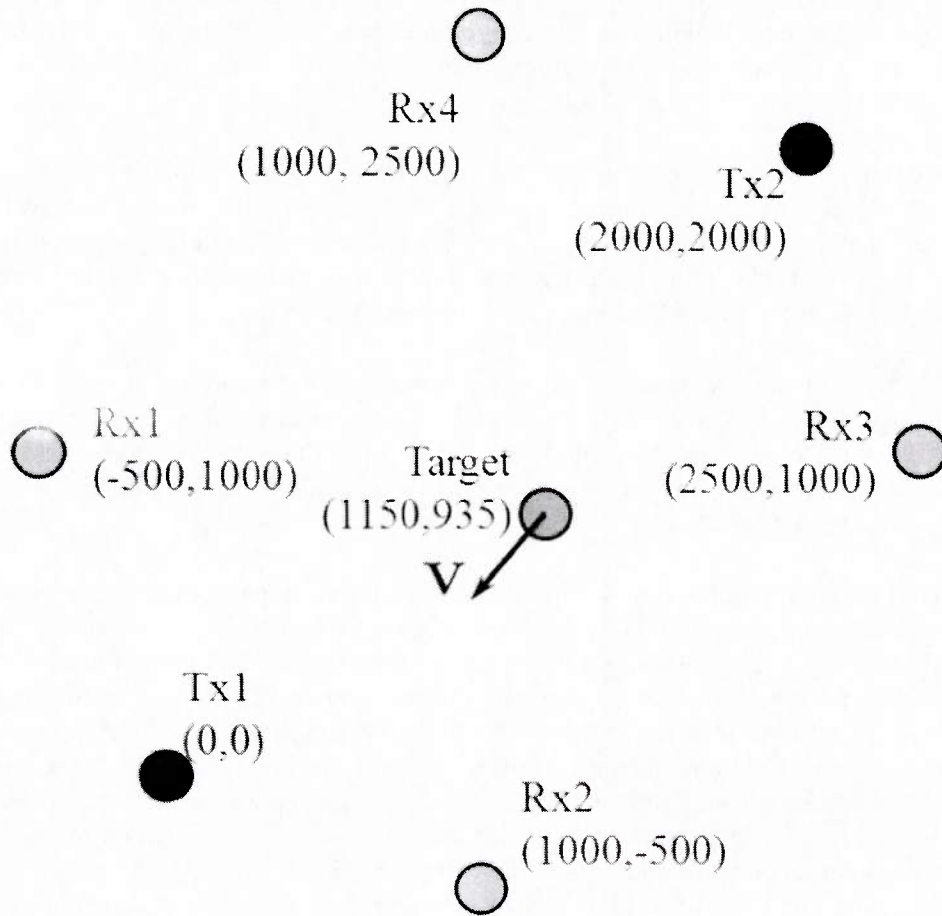


Figure 1. The simulation geometry.

[graph: The coordinate vectors of the four receivers Rx1, Rx2, Rx3, and Rx4 are $r1 = [-500, 1000]$, $r2 = [1000, -500]$, $r3 = [2500, 1000]$, and $r4 = [1000, 2500]$, respectively (the unit of distance is meter). Two transmitters, Tx1 and Tx2, are located at $t1 = [0, 0]$ and $t2 = [2000, 2000]$, respectively. A target, located at $[1150, 935]$, is moving in the field of view at a velocity of $v = [-1.8/\sqrt{2}, -1.8/\sqrt{2}]$ knots.]

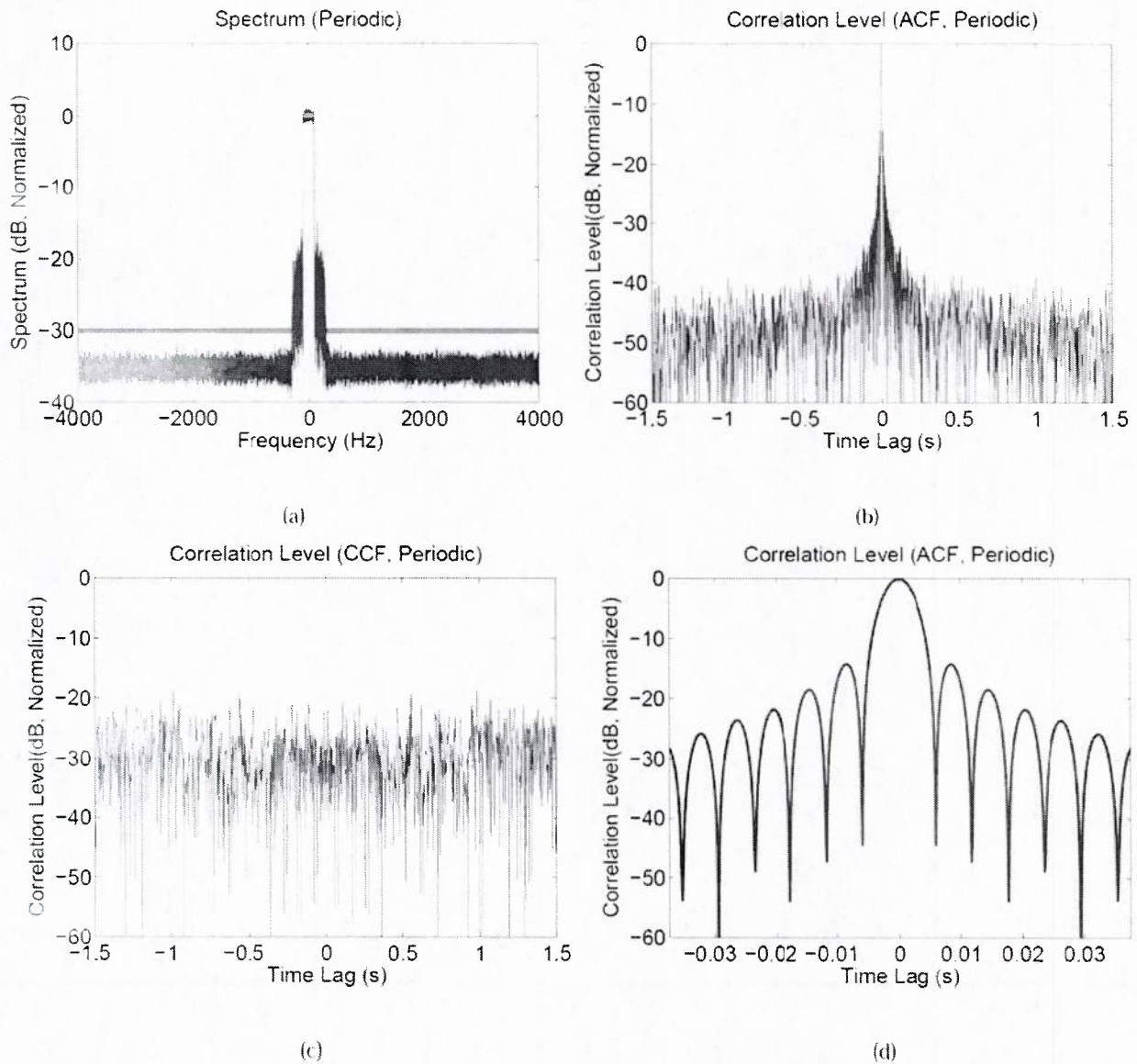


Figure 2. Spectrum, ACF, CCF, and zoomed-in ACF of periodic continuous sequences.

[graph: The spectrally constrained periodic continuous probing waveforms satisfy the stopband restrictions strictly. The ACF of the waveforms has low sidelobe levels. The CCF level is low as well.]

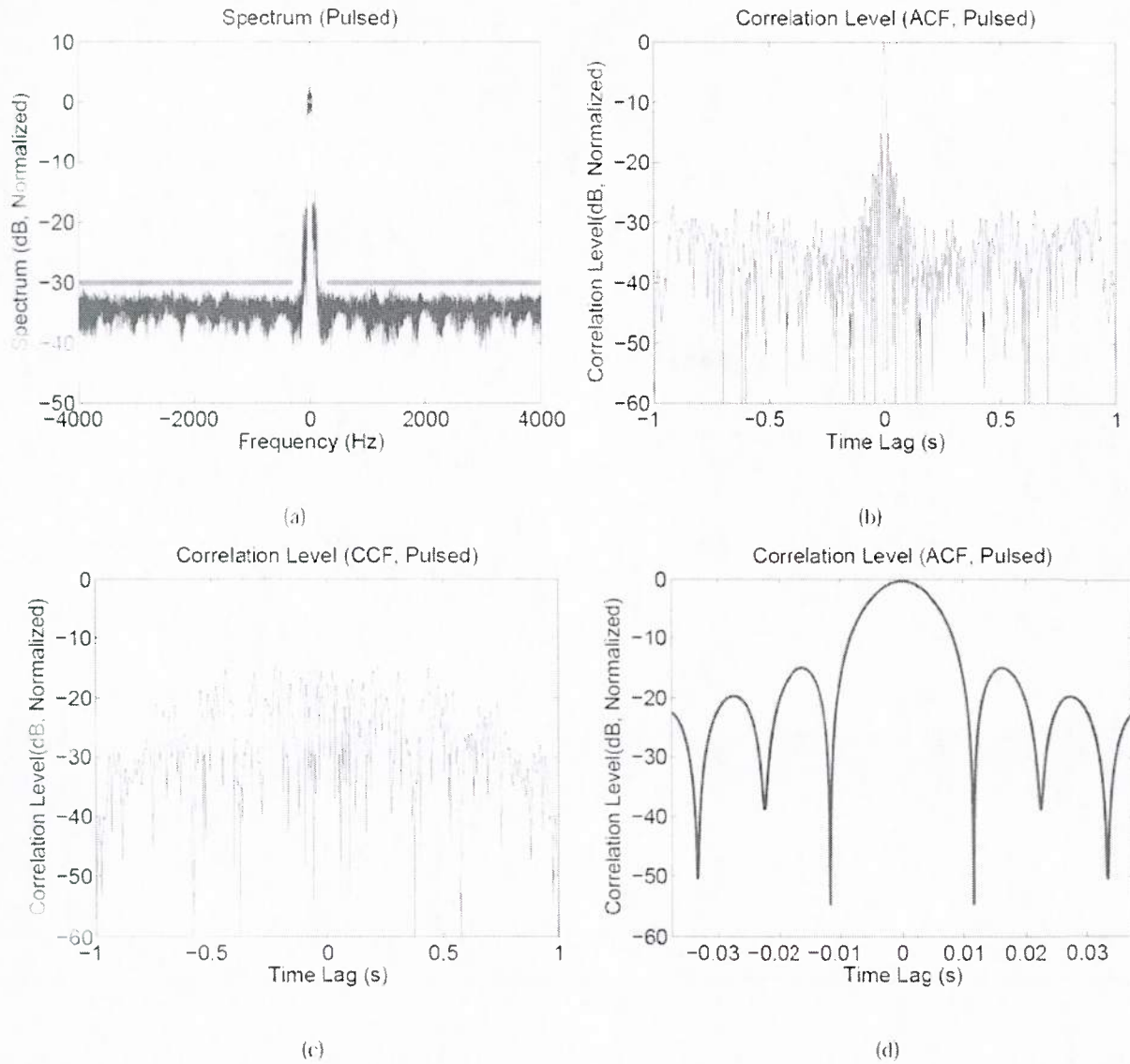


Figure 3. Spectrum, ACF, CCF, and zoomed-in ACF of pulsed sequences.

[graph: The spectrally constrained pulsed probing waveforms satisfy the stopband restrictions strictly. The passband of the pulsed sequences are much narrower than that of their continuous counterparts in Figure 2. The ACF of the waveforms has low sidelobe levels but the mainlobe width is much wider than that of their continuous counterparts in Figure 2. Wider ACF mainlobe means poorer range resolution. The CCF level of the pulsed sequences is higher than that of their continuous counterparts in Figure 2. Higher CCF level indicates stronger mutual interferences among transmitted probing sequences.]

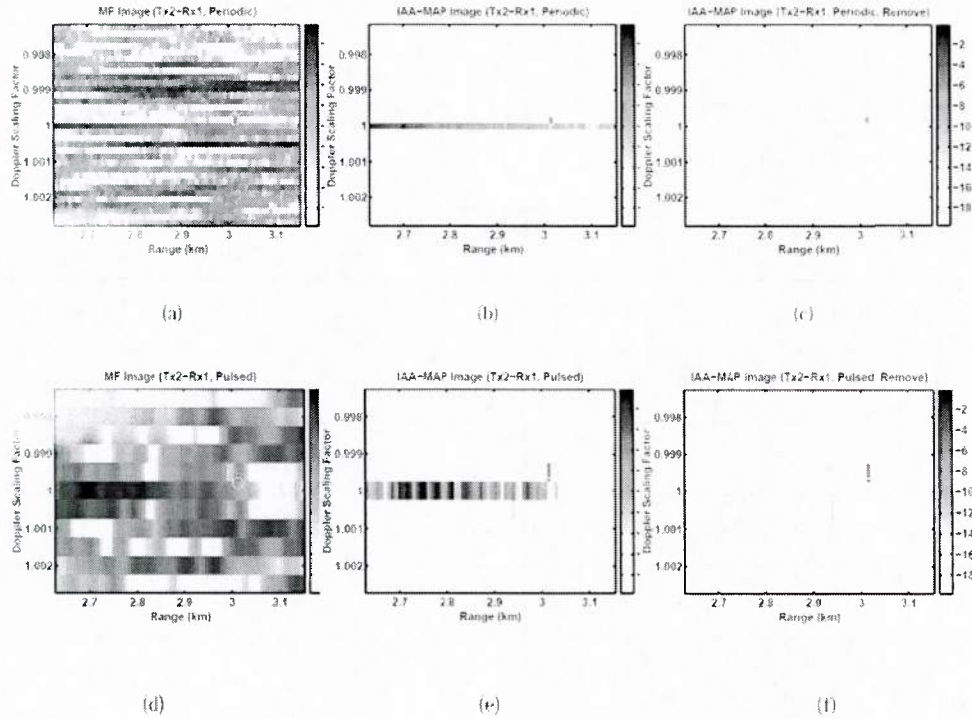


Figure 4. Range-Doppler images produced by a multistatic continuous active sonar system using various probing waveforms. Circles indicate the true locations of the target. First row: periodic continuous waveforms; second row: pulsed waveforms. First column: matched filter (MF) receiver; second column: IAA-MAP; third column: IAA-MAP with stationary background removed.

[graph: Continuous probing waveforms provide range-Doppler images with higher resolution than their pulsed counterparts.

The data-adaptive IAA-MAP algorithm possesses excellent interference suppression capabilities and produce much sharper images than the conventional data-independent MF approach.]

Table I. REFLECTION COEFFICIENTS AND NOISE VARIANCE.

With respect to Rx1					With respect to Rx2				
$ \kappa_{1,1} $	$ \kappa_{2,1} $	DB _{1,1}	DB _{2,1}	VA ₁	$ \kappa_{1,2} $	$ \kappa_{2,2} $	DB _{1,2}	DB _{2,2}	VA ₂
0.5	0.53	0.99	0.99	0.05	0.53	0.57	0.99	0.99	0.05
With respect to Rx3					With respect to Rx4				
$ \kappa_{1,3} $	$ \kappa_{2,3} $	DB _{1,3}	DB _{2,3}	VA ₃	$ \kappa_{1,4} $	$ \kappa_{2,4} $	DB _{1,4}	DB _{2,4}	VA ₄
0.6	0.63	0.99	0.99	0.05	0.47	0.43	0.99	0.99	0.05

Table II. The system parameters.

underwater sound speed	1500 m/s
duration time of Pulsed sequences	1 s
period length of Periodic sequences	3 s
sampling frequency at transmitter	8000 Hz
sampling frequency at receiver	200 Hz

TRANSITIONS

We have provided several CAN sequences to Dr. Michael S. Datum of the Applied Physical Sciences Corporation. He has used some of the sequences as active sonar probing sequences and generated simulated datasets for ASW scenarios using the sonar simulation toolset (SST). He has also used the sequences for in-water experimentations.

We have participated the TREX-CAS in-water experimentation in 2013. We are looking forward to analyze the experimental data collected during the experimentation.

We have also sent our probing waveform synthesis papers to Dr. James Alsup (alsup@cox.net) and our IAA papers to Dr. Roy Streit (streit@metsci.com).

RELATED PROJECTS

NONE.

PUBLICATIONS

Book

H. He, J. Li, and P. Stoica, *Waveform Design for Active Sensing Systems -- A computational approach*, Cambridge University Press, 2012. [published, refereed].

Journal Publications

K. Zhao, J. Liang, J. Karlsson, and J. Li, "Enhanced Multistatic Active Sonar Signal Processing," *The Journal of the Acoustical Society of America*, Vol. 134, No. 1, pp. 300-311, July 2013. [published, refereed].

L. Xu, K. Zhao, J. Li, and P. Stoica, "Wideband Source Localization Using Sparse Learning via Iterative Minimization," *Signal Processing*, Vol. 93, No. 12, pp. 3504-3514, December 2013. [published, refereed].

J. Ling, L. Xu, and J. Li, "Adaptive Range-Doppler Imaging and Target Parameter Estimation in Multistatic Active Sonar Systems," *IEEE Journal of Oceanic Engineering*. [in press, refereed].

J. Liang, L. Xu, J. Li, and P. Stoica, "On Designing the Transmission and Reception of Multistatic Continuous Active Sonar Systems," *IEEE Transactions on Aerospace and Electronic Systems*. [in press, refereed].

Conference Publications

K. Zhao, J. Liang, J. Karlsson, and J. Li, "Enhanced Multistatic Active Sonar Signal Processing," *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Vancouver, Canada, May 26-31, 2013. [published, refereed].

J. Li. "On Designing the Transmission and Reception of Multistatic Continuous Active Sonar Systems," *2013 IEEE Underwater Acoustic Signal Processing Workshop*, West Greenwich, Rhode Island, October 16-18, 2013. [invited]

HONORS/AWARDS/PRIZES

Dr. Jian Li gave a plenary talk at the IEEE Sensor Array and Multichannel Signal Processing Workshop, in Hoboken NJ, in June 2012.