

RPPR Final Report

as of 28-Mar-2022

Agency Code: 21XD

Proposal Number: 77724EL

Agreement Number: W911NF-20-2-0271

INVESTIGATOR(S):

Name: Christopher Allen
Email: callen@ku.edu
Phone Number: 7858648801
Principal: N

Name: Shannon Blunt Phd
Email: sdblunt@ku.edu
Phone Number: 7858647326
Principal: Y

Organization: **University of Kansas**

Address: 2385 Irving Hill Road, Lawrence, KS 660457568

Country: USA

DUNS Number: 076248616

EIN: 480680117

Report Date: 14-Dec-2021

Date Received: 18-Mar-2022

Final Report for Period Beginning 15-Sep-2020 and Ending 14-Sep-2021

Title: Waveform Diversity for Complex Environments

Begin Performance Period: 15-Sep-2020

End Performance Period: 14-Sep-2021

Report Term: 0-Other

Submitted By: Shannon Blunt

Email: sdblunt@ku.edu

Phone: (785) 864-7326

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0

STEM Participants: 3

Major Goals: In conjunction with the Spectrum Access Sensor for Situational analysis (SASSY) program from OUSD(R&E) rapid reaction technology office (RRTO) being led by the Army Research Laboratory (ARL), this effort is investigating advanced methods for array processing and signal identification. This work also involves experimental evaluation in test equipment hardware and an RF system-on-a-chip (RF-SoC) to provide a physically meaningful feedback loop for further theoretical development.

The major SASSY-associated goals therefore include:

- Demonstrate advanced direction-finding in ultrasonic and RF hardware using theoretically developed reiterative minimum mean-square error (RMMSE) estimation algorithms;
- Develop and demonstrate a time-frequency version of RMMSE estimation to realize an adaptive spectrogram capability for enhanced signal identification;
- Formulation and demonstrate a joint space/frequency version of RMMSE that performs both direction-finding and enhanced signal estimation, with the joint nature providing improved separability;
- Investigate the possible estimation enhancements that can be achieved when using distributed receivers performing the methods above;
- Investigate further expansions of these methods to incorporate other degrees of freedom.

Separate from the SASSY effort we are also exploring:

- The development of advanced received processing to improve separability between intermodulation and harmonic responses arising in nonlinear radar.

Accomplishments: Enhanced Receive Processing for Nonlinear Intermodulation Radar

The intermodulation form of nonlinear radar, developed under previous ARO support (see [1,2]) relies on the high dimensionality provided by nonrepeating waveform pairs generated by separate, yet collocated, transmitters. Because each transmitter also unavoidably produces a nonlinear second-harmonic version of each waveform it emits at the fundamental frequency, these harmonics become the dominant source of interference to the detection of intermodulation signals produced by mixing of the two fundamental waveforms in a hypothetical device under test (DUT). While the high dimensionality afforded by the aggregate time-bandwidth product of these nonrepeating waveform pairs provides separability from the harmonic interference, there is a desire to achieve separability at

RPPR Final Report as of 28-Mar-2022

somewhat lower dimensionality to facilitate operation over shorter time scales and narrower bandwidths. To address this problem, we are investigating the use of various waveform-dependent cancellation methods in the intermodulation receiver. Specifically, since knowledge of the transmitter harmonics can be obtained via direct loopback capture of each emission, robust versions of the CLEAN technique are being examined. To further improve fidelity for cancellation, we are also exploring the application of adaptive pulse compression (APC) in this context. Simulation results of these methods indicate 10-20 dB of improvement is possible, with experimental loopback capture planned for the near term.

Adaptive Direction-Finding

The re-iterative super-resolution (RISR) method was previously developed at KU as a way to perform adaptive beamforming. It is a particular instantiation of the reiterative minimum mean-square error (RMMSE) estimation technique derived several years ago by PI Blunt, which has been successfully modified, applied, and in some cases actively deployed for radar pulse compression, sonar, magnetoencephalography (MEG) brain imaging, multistatic radar spectrum sharing, fast-time clutter cancellation, and more. The application to direction-finding, while theoretically straightforward on its face, necessitates consideration of array calibration limitations and the unavoidable model errors that ensue. Consequently, it is necessary to incorporate robustness attributes into the iterative algorithmic structure, including a “partial” gain constraint to balance between super-resolution and possible over-suppression of different signal components, an array calibration procedure to account for estimable gain/phase errors at each element, and a signal-dependent tolerance control for unknowable model error that accounts for associated “multiplicative noise” effects.

Collectively, these robustness measures convert a theoretically interesting, yet limited in practice algorithm into a powerful tool that can directly estimate the number, direction, and complex signal structure of far-field sources over a meaningful dynamic range from measured data. Experimental result using both ultrasonic and RF testbeds have been used to repeatedly test different data collection configurations and algorithmic implementation variations. For instance, Fig. 1 illustrates experimental results involving three emitters producing FMCW, OFDM, and random FM signals captured by an 8-element high-speed oscilloscope. The left panel shows how the traditional MVDR spatial estimate realizes a rather smeared response, while the RISR estimate in the right panel shows clear spatial delineation between the signals, with the sweep of the LFM very evident at a spatial angle of $\odot 20^\circ$.

Adaptive Signal Estimation/Identification

We have likewise been exploring a time-frequency version of RISR for the purpose of formulating an adaptive spectrogram capability (and perhaps other adaptive transformations to follow). Figures 2 and 3 depict standard and adaptive spectrograms for the FMCW and random FM waveforms captured above after separation using adaptive direction-finding. The adaptive version clearly suppresses the sidelobes while potentially enabling determination of fine details that would have otherwise been obscured due to resolution enhancement. Indeed, it is important to note that the time-varying nature of these signals means this manner of signal improvement can only be achieved by using an approach like RISR (or RMMSE in general) that operates on each individual data snapshot, as opposed to classical methods that employ sample covariance matrices and therefore must rely on signal stationarity.

Preliminary results indicate that further enhancement is achievable when joint time/frequency adaptive processing is performed in this way, where the multiplicative increase in degrees of freedom enables greater signal separation capability. It also stands to reason that expansion to other signal domains (e.g. polarization), the consideration across multiple levels of resolution trade-off (i.e. spectrogram window size), and other time-frequency transforms (e.g. Wigner-Ville) could potentially be examined through this structured adaptivity lens. In other words, this work highlights the importance of performing 6.1 basic research within the context of experimental measurements and hardware implementation so that advanced theoretical capabilities can be brought to bear on useful problems.

References

- [1] J. Owen, S.D. Blunt, K. Gallagher, P. McCormick, C. Allen, K. Sherbondy, “Nonlinear radar via intermodulation of FM noise waveform pairs,” IEEE Radar Conf., Oklahoma City, OK, 23-27 Apr. 2018.
- [2] J. Owen, C. Mohr, S.D. Blunt, K. Gallagher, “Nonlinear radar via intermodulation of jointly optimized FM noise waveform pairs,” IEEE Radar Conference, Boston, MA, 22-26 Apr. 2019.

RPPR Final Report as of 28-Mar-2022

Training Opportunities: Graduate student Jon Owen (PhD EE) spent summer 2021 at MIT Lincoln Laboratory where he further developed skills in real-time software-defined RF implementation. Graduate student Christian Jones (PhD EE) spent the summer 2021 at the Naval Research Laboratory where he continued to develop signal processing research skills. Graduate Student Zeus Gannon (MS EE) spent summer 2021 at NSWC Dahlgren where he continued to develop RF engineering skills.

Results Dissemination: Results of this research have been published in the following venues (for the current year):

Book

S.D. Blunt, E.S. Perrins, Radar & Communication Spectrum Sharing, SciTech Publishing, 2018.

Journal

B. Ravenscroft, J.W. Owen, J. Jakabosky, S.D. Blunt, A.F. Martone, and K.D. Sherbondy, "Experimental demonstration and analysis of cognitive spectrum sensing & notching," IET Radar, Sonar & Navigation, vol. 12, no. 12, pp. 1466-1475, Dec. 2018. (special issue on Cognitive Radar)

Conference

J. Owen, C. Mohr, S.D. Blunt, K. Gallagher, "Nonlinear radar via intermodulation of jointly optimized FM noise waveform pairs," IEEE Radar Conference, Boston, MA, 22-26 Apr. 2019.

B. Ravenscroft, J.W. Owen, S.D. Blunt, A.F. Martone, K.D. Sherbondy, "Optimal mismatched filtering to address clutter spread from intra-CPI variation of spectral notches," IEEE Radar Conference, Boston, MA, 22-26 Apr. 2019.

J.W. Owen, B. Ravenscroft, S.D. Blunt, "Devoid clutter capture and filling (DeCCaF) to compensate for intra-CPI spectral notch variation," International Radar Conference, Toulon, France, 23-27 Sept. 2019.

Thesis

D.M. Hemmingsen, "Waveform-diverse stretch processing," MS EE thesis, University of Kansas, 27 March 2019.

Honors and Awards: In May 2021 PI Blunt was selected as one of the five short-listed finalists for the IET A.F. Harvey Prize in the field of radar and microwave engineering (given once every three years). The final decision is expected to be announced in Fall 2021.

Protocol Activity Status:

Technology Transfer: In collaboration with Tony Martone and Kelly Sherbondy of ARL, the KU-developed re-iterative super-resolution (RISR) algorithm has been further developed and evaluated experimentally to provide enhanced direction-finding, natural array calibration, and improved signal estimation. A technology demonstration of these capabilities to OUSD(R&E) will occur in Sept. 2021. The implementation code, in Matlab, C++, and CUDA formats, is being prepared to share with OUSD(R&E).

PARTICIPANTS:

Participant Type: PD/PI

Participant: Shannon Blunt

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

Participant: Chris Allen

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

RPPR Final Report
as of 28-Mar-2022

Participant Type: Graduate Student (research assistant)
Participant: Zeus Gannon
Person Months Worked: 8.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Christian Jones
Person Months Worked: 8.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Jon Owen
Person Months Worked: 8.00
Project Contribution:
National Academy Member: N
Funding Support:

Partners

I certify that the information in the report is complete and accurate:
Signature: Shannon Blunt
Signature Date: 3/18/22 5:10PM

Year 1 Accomplishments

Enhanced Receive Processing for Nonlinear Intermodulation Radar

The intermodulation form of nonlinear radar, developed under previous ARO support (see [1,2]) relies on the high dimensionality provided by nonrepeating waveform pairs generated by separate, yet collocated, transmitters. Because each transmitter also unavoidably produces a nonlinear second-harmonic version of each waveform it emits at the fundamental frequency, these harmonics become the dominant source of interference to the detection of intermodulation signals produced by mixing of the two fundamental waveforms in a hypothetical device under test (DUT). While the high dimensionality afforded by the *aggregate time-bandwidth product* of these nonrepeating waveform pairs provides separability from the harmonic interference, there is a desire to achieve separability at somewhat lower dimensionality to facilitate operation over shorter time scales and narrower bandwidths.

To address this problem, we are investigating the use of various waveform-dependent cancellation methods in the intermodulation receiver. Specifically, since knowledge of the transmitter harmonics can be obtained via direct loopback capture of each emission, robust versions of the CLEAN technique are being examined. To further improve fidelity for cancellation, we are also exploring the application of adaptive pulse compression (APC) in this context. Simulation results of these methods indicate 10-20 dB of improvement is possible, with experimental loopback capture planned for the near term.

Adaptive Direction-Finding

The re-iterative super-resolution (RISR) method was previously developed at KU as a way to perform adaptive beamforming. It is a particular instantiation of the reiterative minimum mean-square error (RMMSE) estimation technique derived several years ago by PI Blunt, which has been successfully modified, applied, and in some cases actively deployed for radar pulse compression, sonar, magnetoencephalography (MEG) brain imaging, multistatic radar spectrum sharing, fast-time clutter cancellation, and more. The application to direction-finding, while theoretically straightforward on its face, necessitates consideration of array calibration limitations and the unavoidable model errors that ensue. Consequently, it is necessary to incorporate robustness attributes into the iterative algorithmic structure, including a “partial” gain constraint to balance between super-resolution and possible over-suppression of different signal components, an array calibration procedure to account for estimable gain/phase errors at each element, and a signal-dependent tolerance control for unknowable model error that accounts for associated “multiplicative noise” effects.

Collectively, these robustness measures convert a theoretically interesting, yet limited in practice algorithm into a powerful tool that can directly estimate the number, direction, and complex signal structure of far-field sources over a meaningful dynamic range from measured data. Experimental result using both ultrasonic and RF testbeds have been used to repeatedly test

different data collection configurations and algorithmic implementation variations. For instance, Fig. 1 illustrates experimental results involving three emitters producing FMCW, OFDM, and random FM signals captured by an 8-element high-speed oscilloscope. The left panel shows how the traditional MVDR spatial estimate realizes a rather smeared response, while the RISR estimate in the right panel shows clear spatial delineation between the signals, with the sweep of the LFM very evident at a spatial angle of -20° .

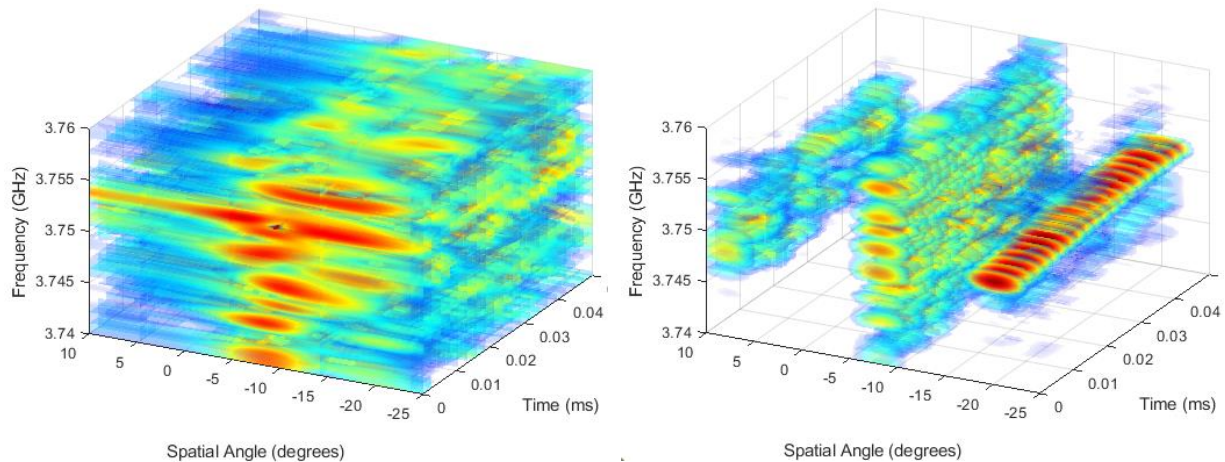


Figure 1: Direction-finding estimate as a function of time, spatial angle, and frequency using (left) MVDR and (right) RISR

Adaptive Signal Estimation/Identification

We have likewise been exploring a time-frequency version of RISR for the purpose of formulating an adaptive spectrogram capability (and perhaps other adaptive transformations to follow). Figures 2 and 3 depict standard and adaptive spectrograms for the FMCW and random FM waveforms captured above after separation using adaptive direction-finding. The adaptive version clearly suppresses the sidelobes while potentially enabling determination of fine details that would have otherwise been obscured due to resolution enhancement. Indeed, it is important to note that the time-varying nature of these signals means this manner of signal improvement can only be achieved by using an approach like RISR (or RMMSE in general) that operates on each individual data snapshot, as opposed to classical methods that employ sample covariance matrices and therefore must rely on signal stationarity.

Preliminary results indicate that further enhancement is achievable when joint time/frequency adaptive processing is performed in this way, where the multiplicative increase in degrees of freedom enables greater signal separation capability. It also stands to reason that expansion to other signal domains (e.g. polarization), the consideration across multiple levels of resolution trade-off (i.e. spectrogram window size), and other time-frequency transforms (e.g. Wigner-Ville) could potentially be examined through this structured adaptivity lens. In other words, this work highlights the importance of performing 6.1 basic research within the context of experimental measurements and hardware implementation so that advanced theoretical capabilities can be brought to bear on useful problems.

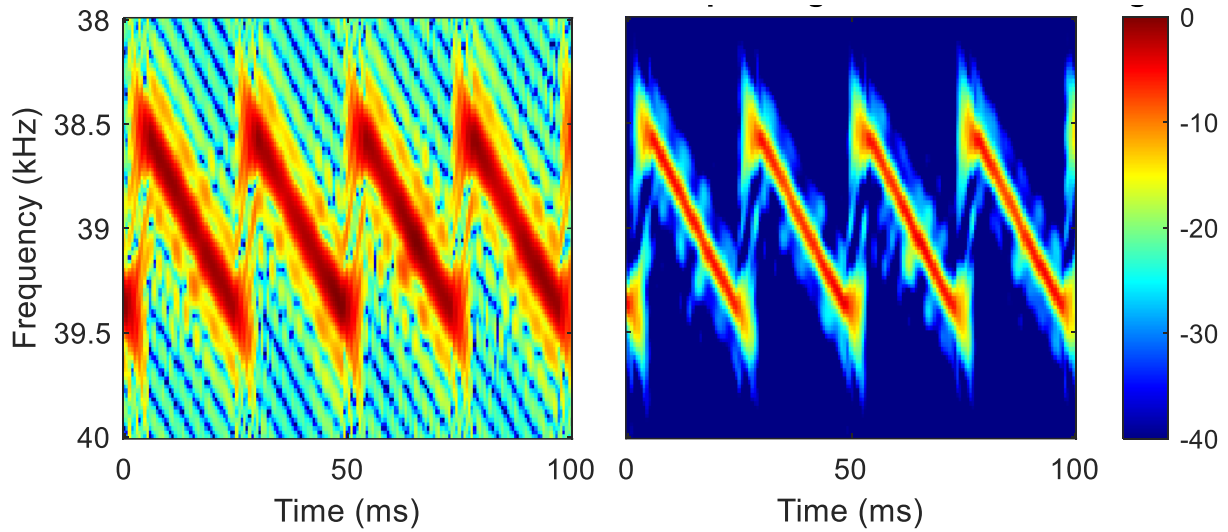


Figure 2: After adaptive direction-finding separation spatially, (left) standard spectrogram and (right) adaptive spectrogram estimation of the open-air captured FMCW signal

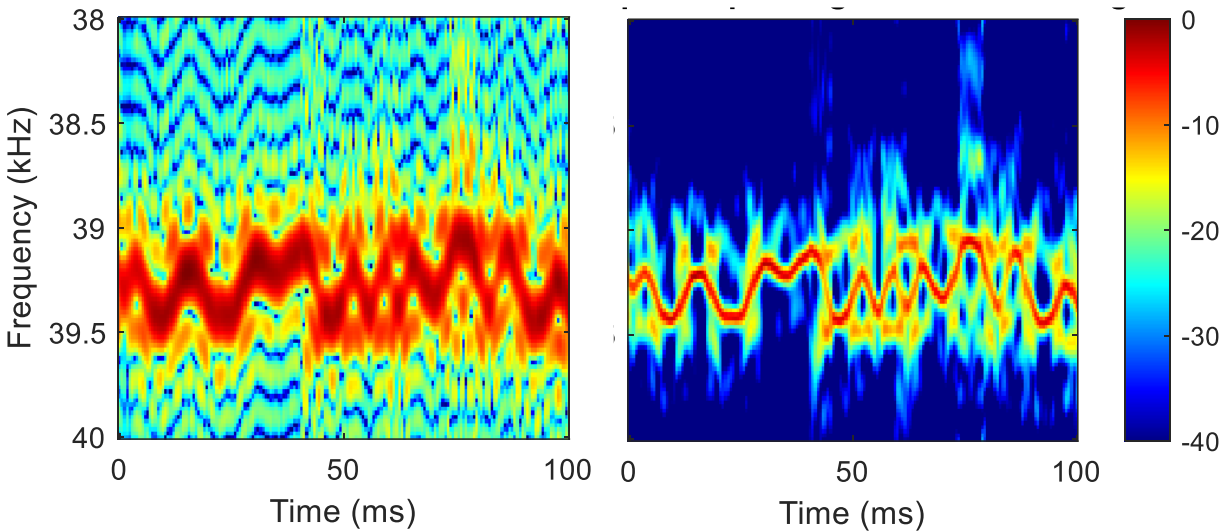


Figure 3: After adaptive direction-finding separation spatially, (left) standard spectrogram and (right) adaptive spectrogram estimation of the open-air captured random FM signal

References

- [1] J. Owen, S.D. Blunt, K. Gallagher, P. McCormick, C. Allen, K. Sherbondy, "Nonlinear radar via intermodulation of FM noise waveform pairs," *IEEE Radar Conf.*, Oklahoma City, OK, 23-27 Apr. 2018.
- [2] J. Owen, C. Mohr, S.D. Blunt, K. Gallagher, "Nonlinear radar via intermodulation of jointly optimized FM noise waveform pairs," *IEEE Radar Conference*, Boston, MA, 22-26 Apr. 2019.