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RPPR Final Report
as of 18-Mar-2020

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STEM Degrees: 1 **STEM Participants:** 3

Major Goals: This effort investigated the development of new solutions to address the need for cognitive radar capabilities to contend with the increasingly congested spectral environment. The work was performed in collaboration with the Army Research Laboratory (ARL) to leverage recent and ongoing work on the optimization of radar operating parameters based on cognitive spectrum sensing.

Specifically, we investigated how previous/ongoing work at the University of Kansas (KU) on the optimization of various physical waveform structures (pulsed, CW, polarization modulation, etc.) could be incorporated into a cognitive sensing paradigm to facilitate the demonstration of a radar that senses the available spectrum, rapidly parameterizes its operating characteristics, and then realizes a suitable physical waveform and associated optimal receive filtering. Performance trade-offs were evaluated in terms of available bandwidth for static and time-varying allocations, contiguous versus fragmented spectral support, and realizable spectral containment for physical transmitters. This analysis was used to inform the determination of appropriate waveform / receive processing structures (including cancellation of non-stationary interference) that are driven by cognitive spectrum sensing. The work also investigated hardware designs, implementations (e.g. software-defined and adaptable transceivers), and assessments of linear and nonlinear sensing for Cognitive Radar.

Accomplishments: The work under this effort generally focused on three main areas:
- Sensing of in-band radio frequency interference (RFI) and subsequent transmit spectral notching by the radar to facilitate spectrum sharing;
- An intermodulation-based approach to nonlinear harmonic radar;
- Generalization of radar stretch processing for chirp-like nonlinear FM waveforms and associated optimal and adaptive implementations.

The topics were investigated both theoretically and experimentally, ultimately leading to the demonstration of methods that could potentially be deployed in real systems. Details are provided in the uploaded report.

Training Opportunities: Year 1
Graduate students Jon Owen and Dana Hemmingsen, and undergraduate student Nichole Hemminsen, spent the summer of 2016 at ARL in Adelphi, MD where they had the opportunity to learn from ARL radar engineers. Jon Owen also attended the 2016 IEEE Radar Conference in Philadelphia, PA where he learned about the current state-of-the-art research in the radar field (in the public domain). PI Shannon Blunt and Co-I Chris Allen attended the 2016 MSS Tri-Service Radar Symposium in Boulder, CO.

Year 2
Graduate student Jon Owen (MSEE) and undergraduate student Eric Schweisberger (BSEE) spent the summer of 2017 at ARL in Adelphi, MD where they had the opportunity to learn from ARL radar engineers. Also, graduate student Garrett Zook (MSEE) spent the 2017 summer working with ARL radar engineers at Aberdeen Proving Ground.
Jon Owen and graduate student Dana Hemmingsen (MSEE) attended the 2017 IEEE Radar Conference in Seattle, WA where they learned about the current state-of-the-art research in the radar field (in the public domain). Jon and Dana are expected to complete their ARO-sponsored MS EE theses this school year as well.
Also, PhD EE student Brandon Ravenscroft has been participating on this effort and the paper he first-authored is a finalist for the Best Student Paper award at the upcoming 2017 IET International Radar Conference in Belfast, UK.

Year 3
Graduate students Jon Owen (now PhD EE) and Dana Hemmingsen (MSEE) attended the 2018 IEEE Radar Conference and presented papers on their ARL-sponsored work on nonlinear harmonic radar, cognitive spectral notching, and stretch processing compensation for NLFM waveforms. Also, PhD EE student Brandon Ravenscroft has been participating on this effort and the paper he first-authored is a finalist for the Best Student Paper award at the upcoming 2017 IET International Radar Conference in Belfast, UK.

Year 4
Graduate students Jon Owen (PhD EE) and Brandon Ravenscroft (PhD EE) attended the 2019 IEEE Radar Conference in Boston, MA and presented papers on their ARL-sponsored work on nonlinear harmonic radar and cognitive spectral notching. Both of these students spent summer of 2019 as interns at the Army Research Laboratory in Adelphi, MD.
Dana Hemmingsen successfully defended her EE Master’s thesis on “Waveform-diverse stretch processing” in March of 2019.

NCE after Year 4
Graduate student Jon Owen (PhD EE) presented his work on cognitive radar clutter modulation compensation at the 2019 International Radar Conference in Toulon, France. He likewise has papers on real-time cognitive radar implementation and waveform optimization for modest fidelity software-defined radios that have been accepted to the 2020 International Radar Conference in Washington, DC.
Graduate student Brandon Ravenscroft (PhD EE) has a paper on range-Doppler joint processing to compensation for clutter modulation from dynamic spectral notching that was accepted to the 2020 International Radar Conference in Washington, DC.

RPPR Final Report
as of 18-Mar-2020

Results Dissemination: Results of this research have been published in the following venues:

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

Journal
S.D. Blunt, J.K. Jakabosky, C.A. Mohr, P.M. McCormick, J.W. Owen, B. Ravenscroft, C. Sahin, G.D. Zook, C.C. Jones, J.G. Metcalf, T. Higgins, “Principles & applications of random FM radar waveform design,” to appear in IEEE AES Systems Magazine.

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)

A. Martone, K. Ranney, K. Sherbondy, and S. Blunt, "Spectrum Allocation for Non-Cooperative Radar Coexistence," IEEE Trans. Aerospace & Electronic Systems, vol. 54, no. 1, pp. 90-105, Feb. 2018.

Conference
J.W. Owen, C.A. Mohr, B.H. Kirk, S.D. Blunt, A.F. Martone, K.D. Sherbondy, “Demonstration of real-time cognitive radar using spectrally-notched random FM waveforms,” IEEE International Radar Conference, Washington, DC, 27-30 Apr. 2020.

J.A. Kovarskiy, J.W. Owen, R.M. Narayanan, S.D. Blunt, A.F. Martone, K.D. Sherbondy, “Spectral prediction and notching of RF emitters for cognitive radar coexistence,” IEEE International Radar Conference, Washington, DC, 27-30 Apr. 2020.

B. Ravenscroft, J.W. Owen, B.H. Kirk, S.D. Blunt, A.F. Martone, K.D. Sherbondy, R.M. Narayanan, “Experimental assessment of joint range-Doppler processing to address clutter modulation from dynamic radar spectrum sharing,” IEEE International Radar Conference, Washington, DC, 27-30 Apr. 2020.

C. Mohr, J. Owen, S.D. Blunt, C.T. Allen, “Zero-order reconstruction optimization of waveforms (ZOROW) for modest DAC rates,” IEEE International Radar Conference, Washington, DC, 27-30 Apr. 2020

A. Dockendorf, A. Egberg, A. Goad, C. Calabrese, B. Adkins, B. Ravenscroft, J. Owen, C. Baylis, S. Blunt, A. Martone, K. Gallagher, R.J. Marks II, “Impedance tuning with notched waveforms for spectrum sharing in cognitive radar,” IEEE International Radar Conference, Washington, DC, 27-30 Apr. 2020.

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.

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.

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. Owen, S.D. Blunt, K. Gallagher, P. McCormick, C. Allen, and K. Sherbondy, "Nonlinear Radar via Intermodulation of FM Noise Waveform Pairs," IEEE Radar Conference, Oklahoma City, OK, 23-27 Apr. 2018.

D.M. Hemmingsen, P.M. McCormick, S.D. Blunt, C. Allen, A. Martone, K. Sherbondy, and D. Wikner, "Waveform-Diverse Stretch Processing," IEEE Radar Conference, Oklahoma City, OK, 23-27 Apr. 2018.

L. Harnett, D. Hemmingsen, P. McCormick, S.D. Blunt, C. Allen, A. Martone, K. Sherbondy, and D. Wikner, "Optimal and Adaptive Mismatch Filtering for Stretch Processing," IEEE Radar Conference, Oklahoma City, OK, 23-27 Apr. 2018.
B. Ravenscroft, S.D. Blunt, C. Allen, A. Martone, and K. Sherbondy, "Analysis of Spectral Notching in FM Noise Radar using Measured Interference," IET International Radar Conference, Belfast, UK, 23-26 Oct. 2017.

B.H. Kirk, J.W. Owen, R.M. Narayanan, S.D. Blunt, A.F. Martone, and K.D. Sherbondy, “Cognitive Software Defined Radar: Waveform Design for Clutter and Interference Suppression,” SPIE Defense + Security Symposium, Anaheim, CA, 9-13 Apr. 2017.

J. Jakabosky, B. Ravenscroft, S.D. Blunt, and A. Martone, "Gapped Spectrum Shaping for Tandem-Hopped Radar/Communications & Cognitive Sensing," IEEE Radar Conf., Philadelphia, PA, 2-6 May 2016.

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

Honors and Awards: The paper below was one of five finalists for the Best Student Paper Award at the conference in October 2017.

- B. Ravenscroft, S.D. Blunt, C. Allen, A. Martone, and K. Sherbondy, "Analysis of spectral notching in FM noise radar using measured interference," IET International Radar Conference, Belfast, UK, 23-26 Oct. 2017.

The paper below was one of five finalists for the Best Student Paper Award at the conference in April 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 April 2019.

For the summer of 2019, KU PhD student Jon Owen (contributor to this research effort) participated in the ARL student research competition. He won the competition at the level of the RF Signal Processing & Modeling Branch, then again at the level of the Electronics & RF Division, and then once again for the entire Sensors & Electron Devices Directorate (SEDD). At the lab-wide competition he ultimately tied for 3rd place.

Protocol Activity Status:

Technology Transfer: In collaboration with Tony Martone and Kelly Sherbondy of ARL, KU-developed FM Noise Radar technology has been transitioned to the Army to support efforts to facilitate the development of cognitive radar and transmit notching of radar emissions. This waveform design scheme has also been implemented into a software defined radar platform.

The following patent application has been filed regarding the devoid clutter capture and filling (DeCCaF) receive processing approach that compensates for the mainlobe modulation of clutter caused by changing the location of spectral notches during the CPI to address dynamic RFI.

- J.W. Owen, G.B. Ravenscroft, S.D. Blunt, "Devoid clutter capture and filling (DeCCaF) to compensate for intra-CPI spectral notch variation," US Patent Application #62/903,618, filed on Sept. 20, 2019

The previous year’s work on stretch processing compensation of NLFM waveforms has also been transitioned to the Air Force where it has been used to facilitate the emerging phase-attached radar/communications (PARC) dual-function emission scheme that, when implemented in an FMCW formulation, has been experimentally demonstrated to achieve 8 MB/s data rate. The stretch compensation approach was used to address the degradation in radar performance that arises from range sidelobe modulation. These results can be found in the references below:

- P.M. McCormick, C. Sahin, J.G. Metcalf, S.D. Blunt, “FMCW implementation of phase-attached radar/communications,” IEEE Radar Conference, Boston, MA, 22-26 Apr. 2019. (not part of this project but included to show the transition)

- C. Sahin, P.M. McCormick, S.D. Blunt, J.G. Metcalf, “Optimized stretch processing compensation for FMCW phase-attached radar-communications,” International Radar Conference, Toulon, France, 23-27 Sept. 2019. (not part of this project but included to show the transition)

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Participant: Shannon Blunt
Person Months Worked: 4.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Jonathan Owen
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant Type: Graduate Student (research assistant)
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Volume: Issue: First Page #:
Date Submitted: 9/12/17 12:00AM Date Published:
Publication Location:
Article Title: Spectrum Allocation for Non-Cooperative Radar Coexistence
Authors: Anthony Martone, Kenneth Ranney, Kelly Sherbondy, Kyle Gallagher, Shannon Blunt
Keywords: cognitive radar
Abstract: Access to the electromagnetic spectrum is an ever-growing challenge for radar. Future radar will be required to mitigate RF interference from other RF sources, relocate to new frequency bands while maintaining quality of service, and share frequency bands with other RF systems. The spectrum sensing, multi-optimization (SS-MO) technique was recently investigated as a possible solution to these challenges. Prior results have indicated significant improvement in the signal-to-interference plus noise ratio (SINR) at the cost of a high computational complexity. However, the optimization computational cost must be manageable in real time to address the dynamically changing spectral environment. In this paper, a bio-inspired filtering technique is investigated to reduce the computational complexity of SS-MO.
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Publication Location: London, UK
Article Title: Experimental demonstration and analysis of cognitive spectrum sensing and notching for radar
Authors: Brandon Ravenscroft, Jonathan Owen, John Jakabosky, Shannon Blunt, Anthony Martone, Kelly Sherb
Keywords: cognitive radar, spectrum sensing, spectral notching
Abstract: Spectrum sensing and transmit notching is a form of cognitive radar that seeks to reduce mutual interference with other spectrum users in the same band. This concept is examined for the case where another spectrum user moves in frequency during the radar's CPI. The physical radar emission is based on a recent FM noise waveform possessing attributes that are inherently robust to sidelobes that otherwise arise for spectral notching. Due to increasing spectrum sharing with cellular communications, the interference considered takes the form of in-band OFDM signals that hop around the band. The interference is measured each PRI and a fast spectrum sensing algorithm determines where notches are required, thus facilitating a rapid response to dynamic interference. Free-space experimental measurements based on notched radar waveforms are collected and synthetically combined with separately measured interference under a variety of conditions to assess the efficacy of such an approach.
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CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2016 IEEE Radar Conference (RadarConf16)
Date Received: 16-Aug-2016 Conference Date: 02-May-2016 Date Published:
Conference Location: Philadelphia, PA, USA
Paper Title: Gapped spectrum shaping for tandem-hopped radar/communications & cognitive sensing
Authors: John Jakabosky, Brandon Ravenscroft, Shannon D. Blunt, Anthony Martone
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Conference Name: SPIE Defense + Security Symposium
Date Received: 09-Jun-2017 Conference Date: 13-Apr-2017 Date Published: 13-Apr-2017
Conference Location: Anaheim, CA, USA
Paper Title: Cognitive Software Defined Radar: Waveform Design for Clutter and Interference Suppression
Authors: Kirk, Benjamin; Owen, Jonathan; Narayanan, Ram; Blunt, Shannon; Martone, Anthony; Sherbondy, Kell
Acknowledged Federal Support: **Y**

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Conference Name: IET International Radar Conference
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Conference Location: Belfast, UK
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Authors: Brandon Ravenscroft, Shannon Blunt, Chris Allen, Anthony Martone, Kelly Sherbondy
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Conference Name: 2018 IEEE Radar Conference
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Paper Title: Experimental Demonstration of Cognitive Spectrum Sensing & Notching for Radar
Authors: Jonathan W. Owen, Brandon Ravenscroft, Benjamin H. Kirk, Shannon D. Blunt, Christopher T. Allen, Ar
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Authors: Jonathan Owen, Shannon D. Blunt, Kyle Gallagher, Patrick McCormick, Christopher Allen, Kelly Sherbo
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Paper Title: Waveform-Diverse Stretch Processing
Authors: Dana M. Hemmingsen, Patrick M. McCormick, Shannon D. Blunt, Christopher Allen, Anthony Martone,
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Date Received: 13-Jun-2018 Conference Date: 24-Apr-2018 Date Published: 11-Jun-2018
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Authors: Lumumba Harnett, Dana Hemmingsen, Patrick M. McCormick, Shannon D. Blunt, Christopher Allen, An
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Paper Title: Nonlinear Radar via Intermodulation of Jointly Optimized FM Noise Waveform Pairs
Authors: Jonathan Owen, Charles Mohr, Shannon D. Blunt, Kyle Gallagher
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Conference Name: 2019 IEEE Radar Conference
Date Received: 06-Jan-2020 Conference Date: 23-Apr-2019 Date Published: 16-Sep-2019
Conference Location: Boston, MA
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Authors: Brandon Ravenscroft, Jonathan W. Owen, Shannon D. Blunt, Anthony F. Martone, Kelly D. Sherbondy
Acknowledged Federal Support: **Y**

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Conference Name: 2019 International Radar Conference
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Conference Location: Toulon, France
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Authors: Jonathan Owen, Brandon Ravenscroft, Shannon D. Blunt
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Authors: Brandon Ravenscroft, Jonathan W. Owen, Benjamin H. Kirk, Shannon D. Blunt, Anthony F. Martone, Ke
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Authors: Jacob A. Kovarskiy, Jonathan W. Owen, Ram M. Narayanan, Shannon D. Blunt, Anthony F. Martone, K
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Authors: Angelique Dockendorf, Austin Egbert, Adam Goad, Caleb Calabrese, Benjamin Adkins, Brandon Raven
Acknowledged Federal Support: **Y**

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Paper Title: Zero-Order Reconstruction Optimization of Waveforms (ZOROW) for Modest DAC Rates
Authors: Charles A. Mohr, Jonathan W. Owen, Shannon D. Blunt, Christopher T. Allen
Acknowledged Federal Support: **Y**

DISSERTATIONS:

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Date Received: 11-Jan-2020 Completion Date: 3/27/19 8:42PM
Title: Waveform-Diverse Stretch Processing
Authors: Dana Hemmingsen
Acknowledged Federal Support: **Y**

PATENTS:

Intellectual Property Type: Patent Date Received: **06-Jan-2020**
Patent Title: Devoid clutter capture and filling (DeCCaF) to compensate for intra-CPI spectral notch variation
Patent Abstract: The DeCCaF method compensates for clutter modulation effects induced when a transmit spect
Patent Number: #62/903,618
Patent Country: USA
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Final Report: Cognitive Radar to Address Spectral Congestion
11 June 2015 – 10 December 2019

PI: Shannon D. Blunt
Co-I: Christopher T. Allen

The work under this effort generally focused on three main areas:

- Sensing of in-band radio frequency interference (RFI) and subsequent transmit spectral notching by the radar to facilitate spectrum sharing;
- An intermodulation-based approach to nonlinear harmonic radar;
- Generalization of radar stretch processing for chirp-like nonlinear FM waveforms and associated optimal and adaptive implementations.

The topics were investigated both theoretically and experimentally, ultimately leading to the demonstration of methods that could potentially be deployed in real systems. The following summarizes the work performed in each area.

Cognitive sense-and-notch (SAN) radar

It is anticipated that RFI arising from the proliferation of 4G/5G and beyond cellular communication systems will be increasingly dynamic with regard to where it resides in the band. Because reliance on a spectrum allocation system that controls DOD usage may not be practical for a variety of reasons (security being primary), the impetus to facilitate practical spectrum sharing may disproportionately fall upon the radar to address. Within this context we have investigated the means through which transmit spectral notching by the radar, based on sensed observation of the current spectral usage, can be realized in practice. The various attributes of this work include:

- An ARL-led approach denoted as fast spectrum sensing (FSS) inspired by the human thalamus that quickly determined spectral occupancy by other users [1];
- The evolution of an approach to realize random FM radar waveforms containing spectral notches associated with the FSS-determined RFI locations, with different versions demonstrated on high-fidelity test equipment as well as a more modest fidelity software-defined radio (SDR) platform (Ettus x310 provided by ARL);
- Observation and analysis of a rather severe clutter modulation effect that goes beyond the simpler range sidelobe modulation (RSM) occurring for nonrepeating waveforms and arises specifically due the movement of spectral notch locations during the radar's coherent processing interval (CPI) to contend with dynamic RFI;
- Development and demonstration of various techniques to compensate for this severe clutter modulation effect;
- Subsequent expansion/acceleration of the overall approach to facilitate real-time operation on the SDR and incorporation into RFI prediction-based architectures.

This effort began with the evaluation of radar performance in [2-4] where spectral notches (gaps) were built into a recently developed class of random FM waveforms [5,6,7]. In this early instantiation, measures to ensure adequate notch depth were required [8] that supplement the otherwise rather shallow notch obtained by the waveform design method in [2,3] alone. Moreover, it was observed that the shape of the notch/gap has a direct impact on the pulse compression range sidelobes, i.e. a rectangular shaped notch introduces a $\sin(x)/x$ sidelobe roll-off that is undesirable (see Fig. 1). When the location of the spectral notch moves during the CPI due to dynamic RFI, an expansion of the range-Doppler point spread function occurs that is the underlying reason for clutter RSM (see Fig. 2). Note that [4] was a finalist for the Best Student Paper at the *IET International Radar Conference* in Belfast, UK.

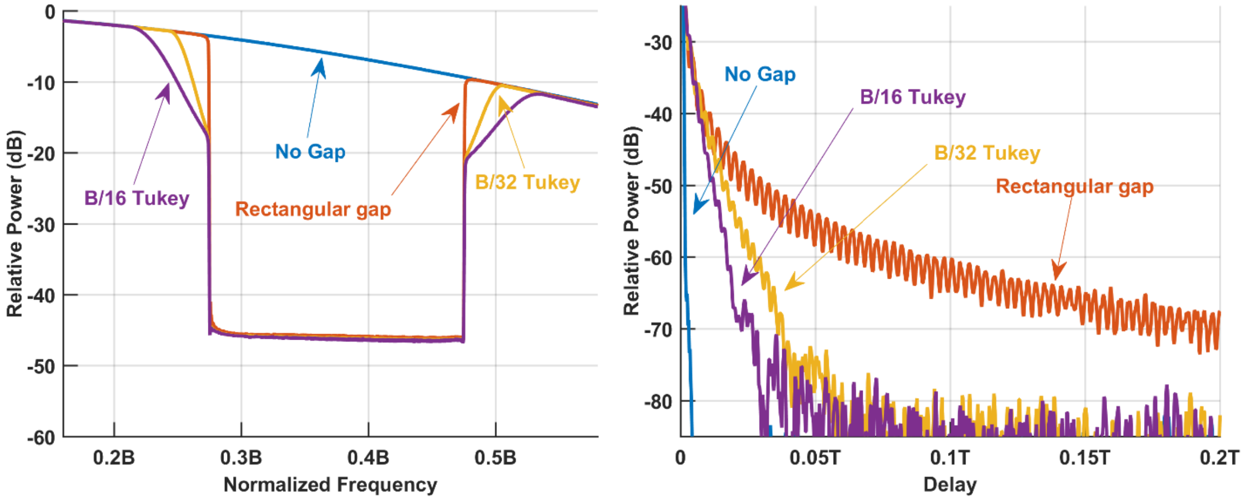

Figure 1: Spectral notch/gap shape inserted into the radar emission (left) leads to corresponding roll-off responses in range sidelobes (right)

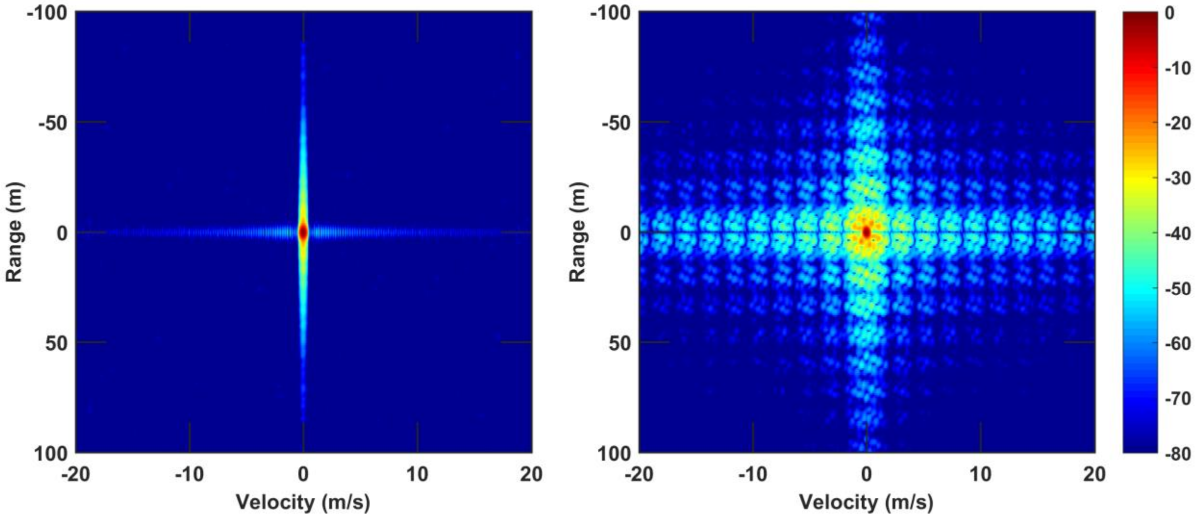

Figure 2: Range-Doppler point spread function for a static spectral notch (left) and a randomly hopping spectral notch due to dynamic RFI (right)

As observed in Fig. 1, tapering of the notch edges provides an effective way in which to compensate for the undesired increase in range sidelobes. It was also noted that the sampling rate of notched waveforms when loading onto an arbitrary waveform generator (AWG) could lead to aliasing that could "fill in" the notch to some degree (Fig. 3). Consequently, the high fidelity required to achieve spectral notching resulted in hardware implementation aspects ultimately influencing the theoretical waveform construction and optimization [9-11].

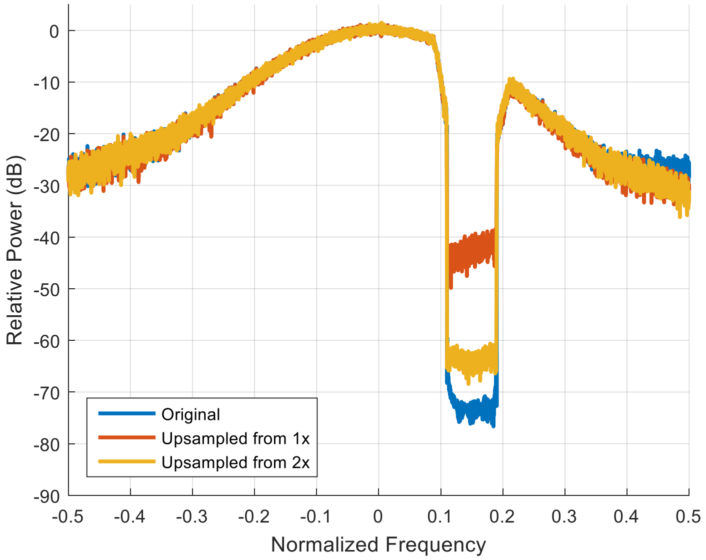

Figure 3: Notching depth according to design sampling rate

This perspective is particularly important when attempting to generate high-fidelity waveforms using modest fidelity hardware such as the SDR. To that end, recent related work by our group [12] was leveraged to develop the zero-order reconstruction optimization of waveforms (ZOROW) method [13] that produces notched waveforms that are suitable to modest digital-to-analog converter (DAC) rate of most SDRs. The particular novelty of this approach is that it reverses the traditional application of Nyquist sampling by facilitating an analytical discretized representation in the frequency domain that can be realized without aliasing because the radar pulse is "time limited" (as opposed to the usual Nyquist notion of bandlimited). Figures 4-6 illustrate simulated along with high and modest fidelity experimental measurements, respectively, of employing this waveform design approach that takes these hardware effects into account. Here the ASpeN approach [12] was recently developed for high-fidelity AWG implementations, and it is a modification of this approach that led to ZOROW [13].

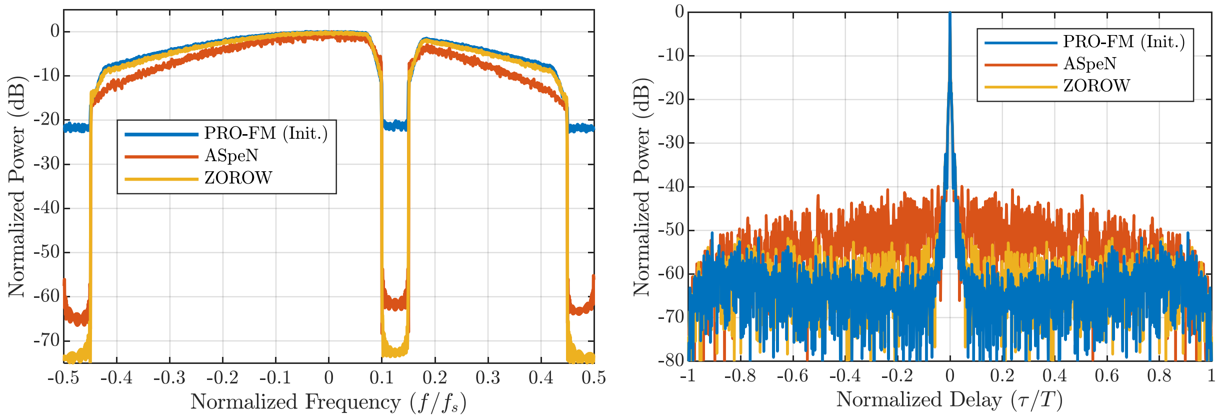

Figure 4: Simulated SDR implementation of notched waveforms from spectral (left) and autocorrelation (right) perspectives

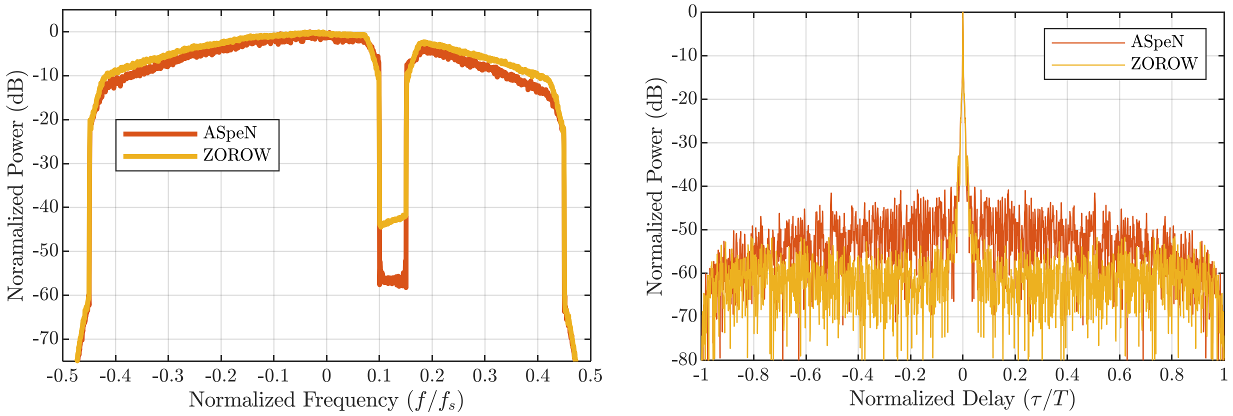

Figure 5: High-fidelity AWG implementation of notched waveforms from spectral (left) and autocorrelation (right) perspectives

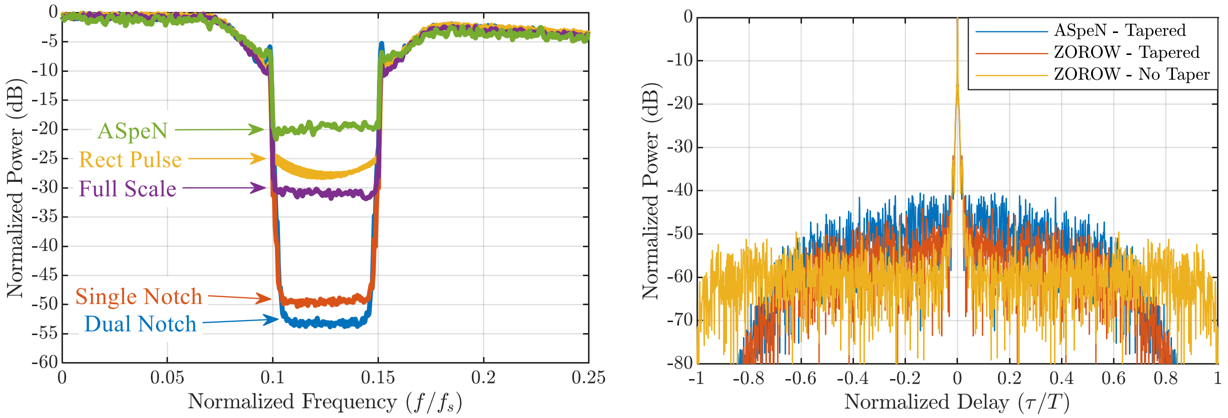

Figure 6: Modest-fidelity SDR implementation of notched waveforms from spectral (left) and autocorrelation (right) perspectives

Implementation fidelity notwithstanding, another important issue that arises with dynamic spectrum notching is clutter modulation, which is a form of nonstationarity that hinders effective clutter cancellation. The simpler form of clutter modulation denoted as range sidelobe modulation (RSM) of clutter [14] occurs when using waveforms that change during a CPI. This manifestation is well-known for random FM waveforms, which serve as a convenient building block for spectral notching since the increased diversity helps to combat increased range sidelobes that are otherwise encountered by notching. However, as illustrated in Fig. 7, when the notches change locations during the CPI a modulation of the autocorrelation mainlobe also arises, which produces the streaking that is observed.

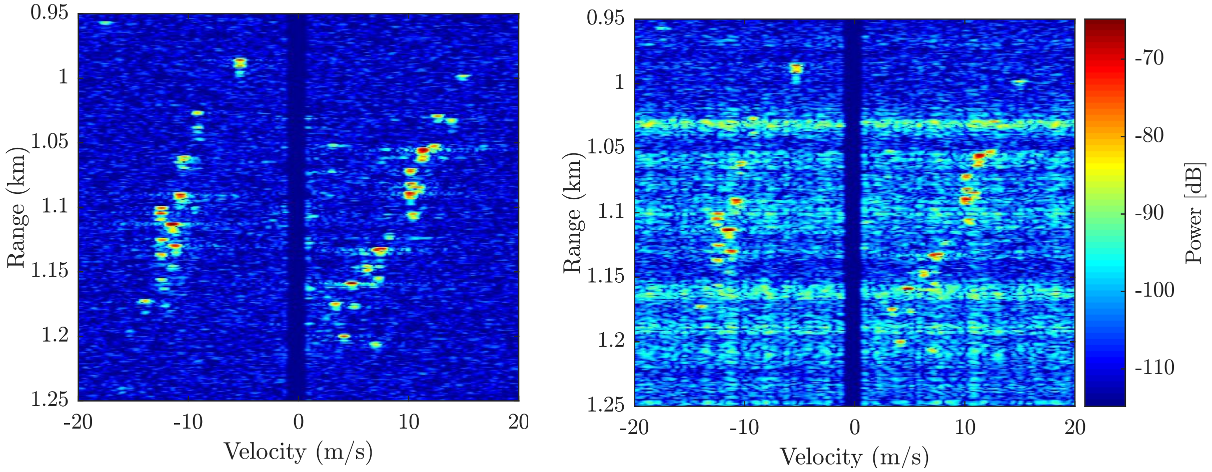

Figure 7: Open-air range-Doppler measurements after simple clutter cancellation using full-band random FM waveforms (left) and random FM waveforms with dynamically changing notch locations (right). RFI is not present so that the clutter modulation effect can be isolated.

When only RSM is present, an effective compensation strategy has been found to be optimal mismatched filtering (MMF) [6], under the caveat that the MMF must take into account the continuous nature of FM waveforms. This effect is actually not even noticeable in Fig. 7 because the use of 2500 unique waveforms for each case provides sufficient dimensionality for simple incoherent sidelobe averaging to be sufficient (it is a different story when the dimensionality is lower; see [6]).

When this approach is applied in an attempt to likewise compensate for dynamic spectral notching [15], however, the impact is rather limited. As shown in Fig. 8, the use of the optimal MMF for each unique notched waveform only marginally reduces the clutter modulation. The reason is because these MMFs do not address the modulation of the autocorrelation mainlobe, which occurs because the notch changes during the CPI and is now the factor limiting performance.

However, combining the MMFs with another new approach, denoted as devoid clutter capture and filling (DeCCaF) [16], does almost completely mitigate the clutter modulation (see Fig. 9). The DeCCaF method borrows the clutter response missing from the notched spectrum in a given waveform response from that produced by a different waveform with a different notch location.

While the statistical independence if slightly violated, the results in Fig. 9 clearly show that the performance is almost negligibly different from the case with no notching at all.

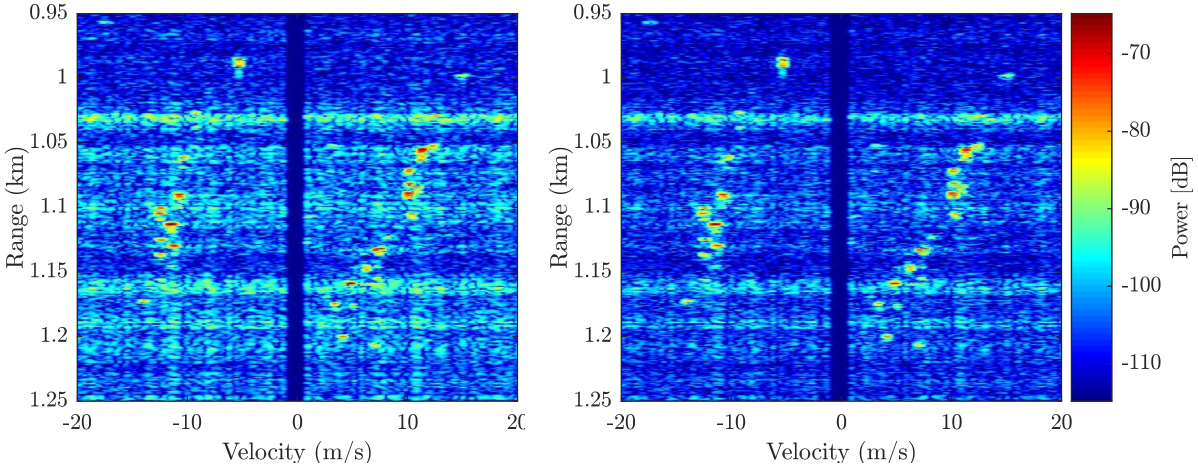

Figure 8: Open-air range-Doppler measurements after simple clutter cancellation using random FM waveforms with dynamically changing notch locations from Fig. 7 when standard matched filtering is used (left) and optimal MMF (right).

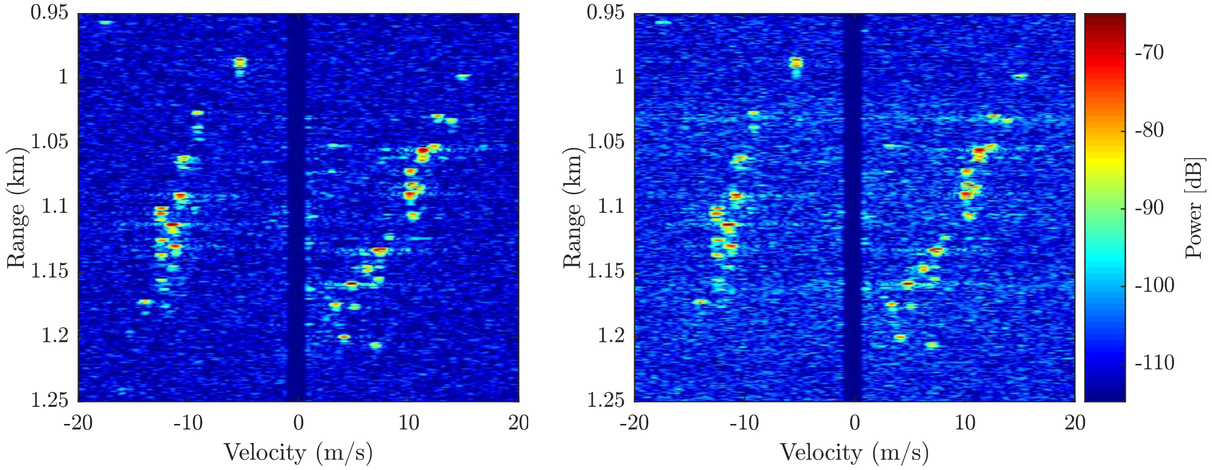

Figure 9: Open-air range-Doppler measurements after simple clutter cancellation using full-band random FM waveforms (left) and random FM waveforms with dynamically changing notch locations compensated using both MMFs and DeCCaF (right).

The previous approach denoted as non-identical multiple pulse compression (NIMPC) [17] has also recently been applied to this problem as a means to compensate for clutter modulation [18]. This method is particularly well-suited to this problem because the underlying cause of clutter modulation is the changing waveform structure from pulse-to-pulse, which is essentially being ignored when the standard processing regiment of pulse compression followed by Doppler processing (including clutter cancellation) are performed. However, when range-Doppler processing are performed in a joint manner (particularly the clutter cancellation) then the associated high dimensional representation has sufficient degrees of freedom to cancel the clutter. From a philosophical perspective, this coupled nature is basically the same reason why space-time adaptive processing (STAP) is generally required to cancel clutter from a moving platform in which the clutter is coupled in angle and Doppler. Of course, as with STAP, the limitation to this approach is computational complexity, though additional work is ongoing to reduce this cost.

The final component of this effort devoted to this research topic focused on how it could be deployed in real-time [19], which introduces additional trade-offs to be considered that translate back into the feasibility of waveform optimization. The prediction of RFI, to the degree possible, has also been examined as a way to circumvent real-time limitations [20]. Later this year these capabilities will be demonstrated to OUSD(R&E). Generally speaking, these results highlight 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.

Optimal/Adaptive Stretch Processing for Arbitrary Chirp-like Waveforms

Stretch processing (or de-chirping) [21] is a well-known method to achieve high range resolution radar without the need to sample a very wideband signal, which might not even be feasible. For use with a linear FM (LFM) waveform, a reference signal having the same constant chirp rate is mixed with the received signal (comprised of a superposition of LFM replicas at different delays and amplitudes), followed lowpass filtering and A/D conversion, and then a fast Fourier transform (FFT). The last stage is exploiting the fact that the mixing output yields a weighted sum of sinusoids.

Our work has investigated how other FM waveforms could likewise leverage the benefits of stretch processing, thereby expanding the portfolio of wideband waveforms that could be used. Because the final FFT stage is essentially just a matched filter bank, one can consider the response that an arbitrary waveform would produce through this progression of mixing with some reference signal, filtering, and sampling, such that the FFT could be replaced by the appropriate "compensation" filter bank that is matched to this response as a function of range delay. This formulation was developed in [22,23].

Figures 10-12 illustrate free-space range-Doppler measurements taken from the roof of Nichols Hall on KU campus for three different chirped FM waveforms using stretch processing. The measurements were not collected at exactly the same time so the movers in the scene are different, yet the results can be compared qualitatively. In Fig. 10 a standard LFM of 7 µs duration and 50 MHz/µs chirp-rate (total swept bandwidth = 350 MHz) is stretch processed with a matching reference, so that this result serves as a performance benchmark.

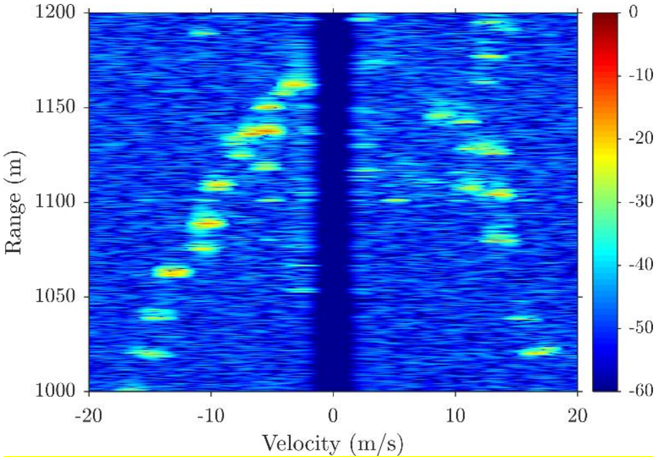

Figure 10: Range-Doppler response for LFM using standard FFT-based stretch processing

In contrast, Fig. 11 (left panel) shows the range smearing that arises from using a piecewise-linear nonlinear FM (NLFM) waveform whose center region has the same 50 MHz/μs chirp-rate as the reference and the beginning/end 1 μs segments have a chirp-rate of 80 MHz/μs (total swept bandwidth = 410 MHz). However, where the left panel of Fig. 2 performs standard FFT stretch processing, the right panel shows what occurs when a compensated transform from [22,23] replaces the FFT. Now the range smearing has been considerably reduced.

As a more extreme example, Fig. 12 shows the use of a piecewise-linear NLFM whose total swept bandwidth is the same 350 MHz as the original LFM, albeit with the same 80 MHz/μs flared edges for the beginning/end 1 μs segments as in the previous case. Thus the center region now has a lower chirp-rate of 38 MHz/μs, so that none of the waveform's chirp-rates actually match that of the 50 MHz/μs reference. Here (Fig. 12, left panel) it is observed that the smearing induced by standard FFT stretch processing is more severe. Once again, however, the use of a compensated transform instead of the FFT provides a way to undo the smearing and sharp target peaks are observed (Fig. 12, right panel).

Note that, while arbitrary waveforms could be used in theory, it is better to employ waveforms that are still chirp-like and are somewhat similar at least to the reference signal. The reason is that, relative to the LFM baseline case, the mixing with another waveform introduces extraneous bandwidth that does not translate directly into range resolution. Essentially, this extra bandwidth is the price that must be paid to be able to use other waveforms, and the amount of that extra bandwidth depends on how dissimilar the waveform is to the reference.

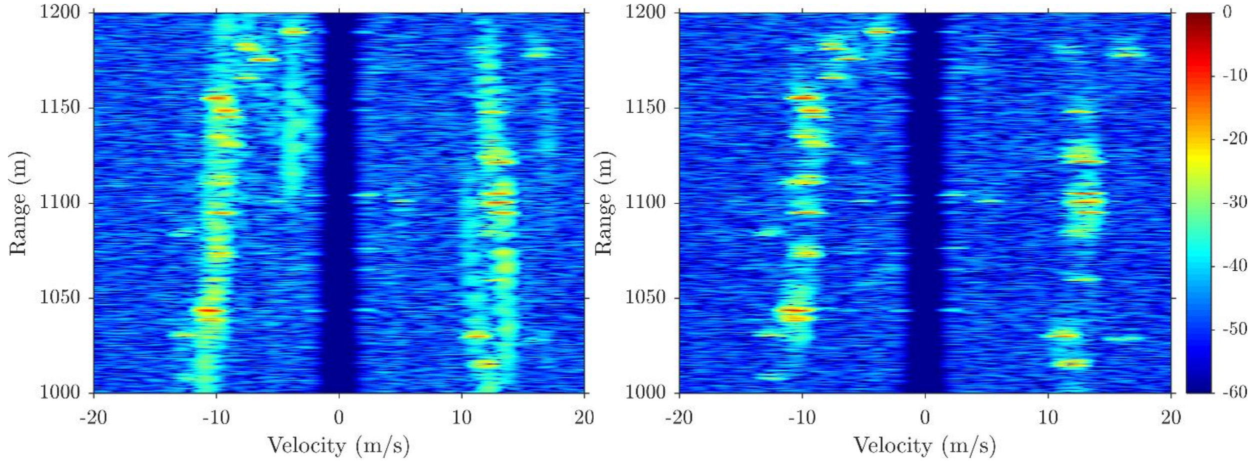

Figure 11: Range-Doppler response for piecewise-linear NLFM where center chirp rate matches the reference. Standard FFT (left) and compensated transform (right).

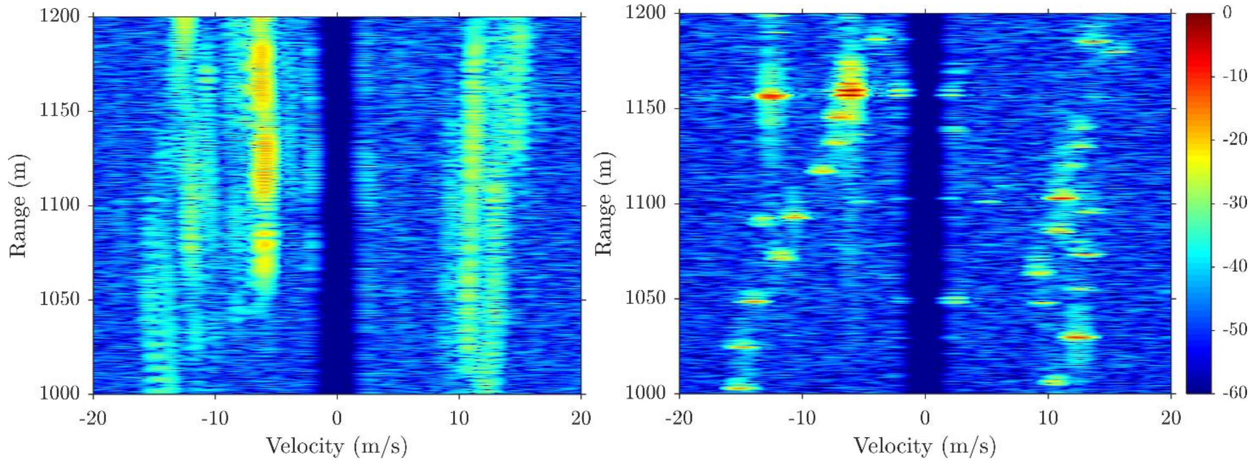

Figure 12: Range-Doppler response for piecewise-linear NLFM where the overall swept bandwidth is the same as the baseline LFM. Standard FFT (left) and compensated transform (right).

While [22,23] developed the capability to compensate for NLFM (yet still chirp-like) waveforms, in [24] two alternatives to the FFT are derived that can be used with either LFM or chirp-like NLFM. The alternatives are based on *a*) a Least-Squares (LS) formulation that our group previously showed can realize the optimal mismatch filter (in the LS sense) for FM waveforms and *b*) an application of our previous work on reiterative minimum mean-square error (RMMSE) estimation. When these formulations are applied to the stretch processing signal structure in the form of filter banks to replace the FFT (i.e. the matched filter bank for LFM), the sidelobes are dramatically reduced (see Fig. 13) while retaining the same resolution and negligible mismatch loss.

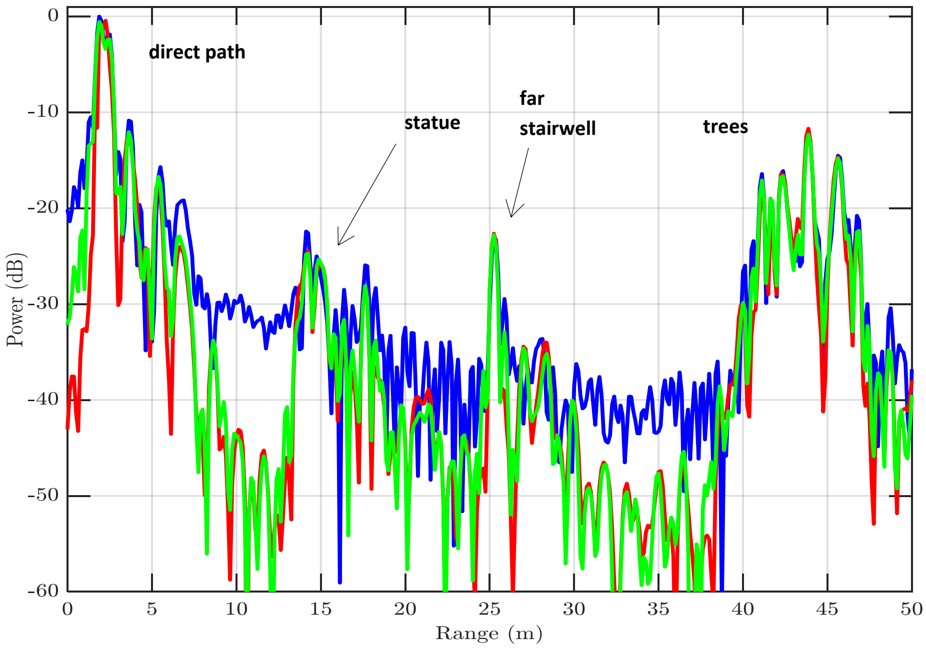

Figure 13: Free-space measurements collected from the roof of Nichols Hall on KU campus (first 50m) using standard stretch processing (blue), LS-based optimum filter bank (green), and RMMSE-based adaptive filter bank (red).

Finally, while not part of the work performed under this effort, it is worth noting that the stretch processing approaches above have also transitioned to a group at the AFRL Sensors Directorate. There they have been used to compensate for RSM of clutter arising from the phase-attached radar/communication (PARC) dual-function emission scheme [25,26].

Intermodulation-Based Nonlinear Harmonic Radar

The last major component of the work performed under this effort involved the development of a new approach to nonlinear harmonic radar involving two random FM waveforms. When these waveforms are simultaneously incident upon a nonlinear device under test (DUT) they realize an intermodulation signal that is separable from their respective harmonic signals (e.g. generated by the transmitters) by virtue of extremely high dimensionality due to each pair of coincident waveforms being unique from all other pairs. The resulting aggregate time-bandwidth product (*BT*) is the individual *BT* for each intermodulated response times the number of pairs. This approach is denoted as shared-spectrum pseudo-random intermodulation (SSPRINT).

In [27] this approach was used with independently generated random FM waveforms, where each pair is denoted as $s_1(t)$ and $s_2(t)$, having associated frequency responses $S_1(f)$ and $S_2(f)$. The harmonic frequency responses are therefore $S_{11}(f)$ and $S_{22}(f)$, and the intermodulation response is $S_{12}(f)$. The measured average power spectra using a wideband amplifier as the nonlinear DUT is shown in Fig. 14, where we observe that the intermodulation component is masked by the two harmonic signals in the same band.

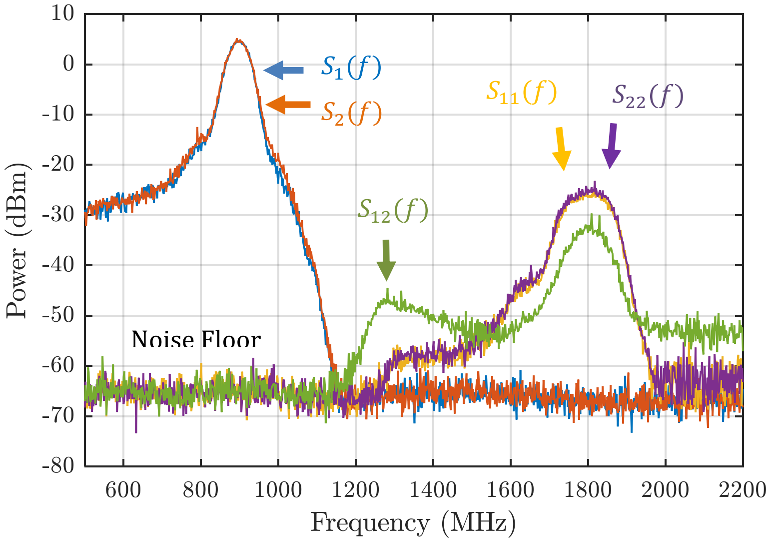

Figure 14: Loopback measured spectrum of the two illuminating waveforms ($S_1(f)$ and $S_2(f)$), their second harmonics ($S_{11}(f)$ and $S_{22}(f)$), and their intermodulation $S_{12}(f)$

Leveraging knowledge of the expected intermodulation signal (based on a power series model), coherent processing of the intermodulation signal can be used to extract this desired signal. As shown in Fig. 15, a single pulse (simultaneous pair of waveforms) provides rather meager separability from the harmonic responses, such that consistent detection would be unlikely. However, the diversity across the waveform pairs, since they do not repeat, provides much greater separation, as illustrated when using 1,000 or even 100,000 unique waveform pairs.

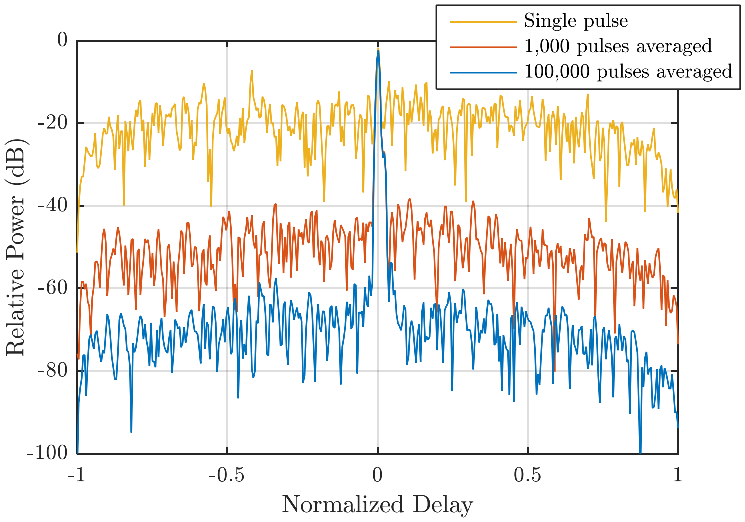

Figure 15: Loopback measurement containing both intermodulation and harmonic responses match filtered with the power series approximation of the intermodulation waveform

Subsequent work [28] then showed that joint optimization of each waveform pair to realize an intermodulation signal that has minimal cross-correlation with the two harmonic signals can provide some additional performance enhancement with regard to separability. The resulting joint SSPRINT (or J-SSPRINT) approach reveals harmonic signals (and thus corresponding original waveforms) whose power spectra possess a shallow notch in the center of the band (see Fig. 16). The consequence of the spectral shaping optimization in the right panel is roughly 5 dB improvement in separability.

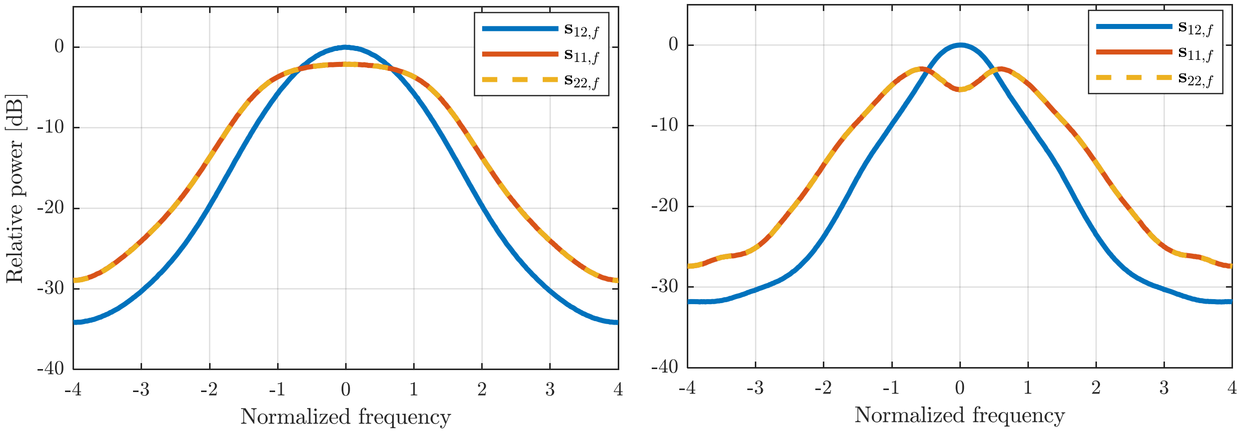

Figure 16: Mean power spectrum over 100,000 unique waveform pairs for the harmonic signals (red and yellow) and intermodulation signals (blue), where the left panel depicts the original SSPRInt formulation and the right panel depicts the J-SSPRInt approach

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