Experimental Assessment of Joint Range-Doppler Processing to Address Clutter Modulation from Dynamic Radar Spectrum Sharing

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High-Level Overview

1. To combat in-band radio-frequency interference (RFI) that is dynamic during the coherent processing interval (CPI) a cognitive radar concept employing agile waveforms has recently been proposed **[1, 2]**.

2. While addressing the RFI issue, these agile waveforms also introduce clutter modulation effects that limit effective clutter cancellation.

3. Here we experimentally examine the impact of joint range-Doppler processing to compensate.

[1] B. Ravenscroft, et al, "Experimental demonstration and analysis of cognitive spectrum sensing and notching for radar," *IET Radar, Sonar & Navigation*, vol. 12, no. 12, pp. 1466-1475, Dec. 2018.

[2] B.H. Kirk, et al, "Avoidance of time-varying radio frequency interference with software-defined cognitive radar," *IEEE Trans. Aerospace & Electronic Systems, vol. 55, no. 3, pp. 1090-1107, June 2019.*

Cognitive Radar Operating Concept

- We consider two types of pulse-agile waveforms to combat in-band RFI within the 3-dB operating band B:
  - **Sense-and-notch (SAN) [1]** constructs spectral notches within B using a nonrepeating sequence of random FM waveforms, thus ***occupying the entire band***
  - **Sense-and-avoid (SAA) [2]** varies center frequency & bandwidth of an LFM waveform to ***occupy the largest available contiguous bandwidth*** within B
  - **Note:** SAN waveforms are more computationally intensive to generate than LFMs for SAA
- Both methods induce clutter smearing when standard processing is applied due to dynamic variation of waveform spectra to address RFI

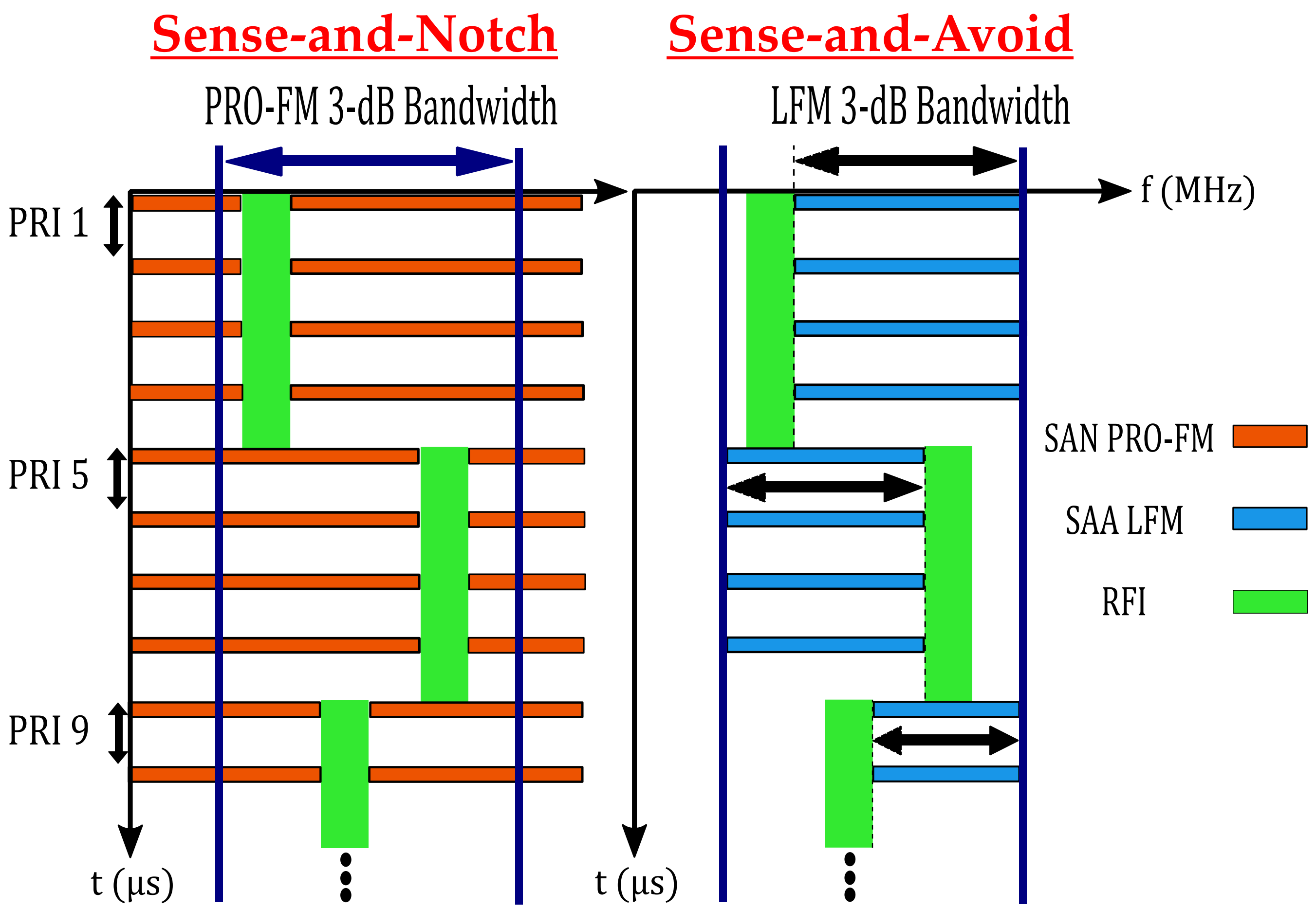
[1] B. Ravenscroft, et al, "Experimental demonstration and analysis of cognitive spectrum sensing and notching for radar," *IET Radar, Sonar & Navigation*, vol. 12, no. 12, pp. 1466-1475, Dec. 2018.

[2] B.H. Kirk, et al, "Avoidance of time-varying radio frequency interference with software-defined cognitive radar," *IEEE Trans. Aerospace & Electronic Systems, vol. 55, no. 3, pp. 1090-1107, June 2019.*

Cognitive Radar Operating Concept

Timing diagram of cognitive operation for SAN and SAA in response to a spectrally dynamic RFI (**green bars**)

- Both approaches rely on fast spectrum sensing (FSS) **[3]** to identify RFI
- SAA waveforms occupy a *portion* of 3-dB bandwidth *B*, with tight roll-off
- SAN waveforms occupy the *entire* band *B*, with Gaussian roll-off (by design)



[3] A.F. Martone, et. al, " Spectrum allocation for noncooperative radar coexistence," *IEEE Trans. Aerospace & Electronic Systems*, vol. 54, no. 1, pp. 90-105, Feb. 2018.

Motivation

- Transmit spectral notching of FM noise waveforms (SAN) and modulation of LFM center frequency & bandwidth (SAA) facilitate dynamic spectrum sharing

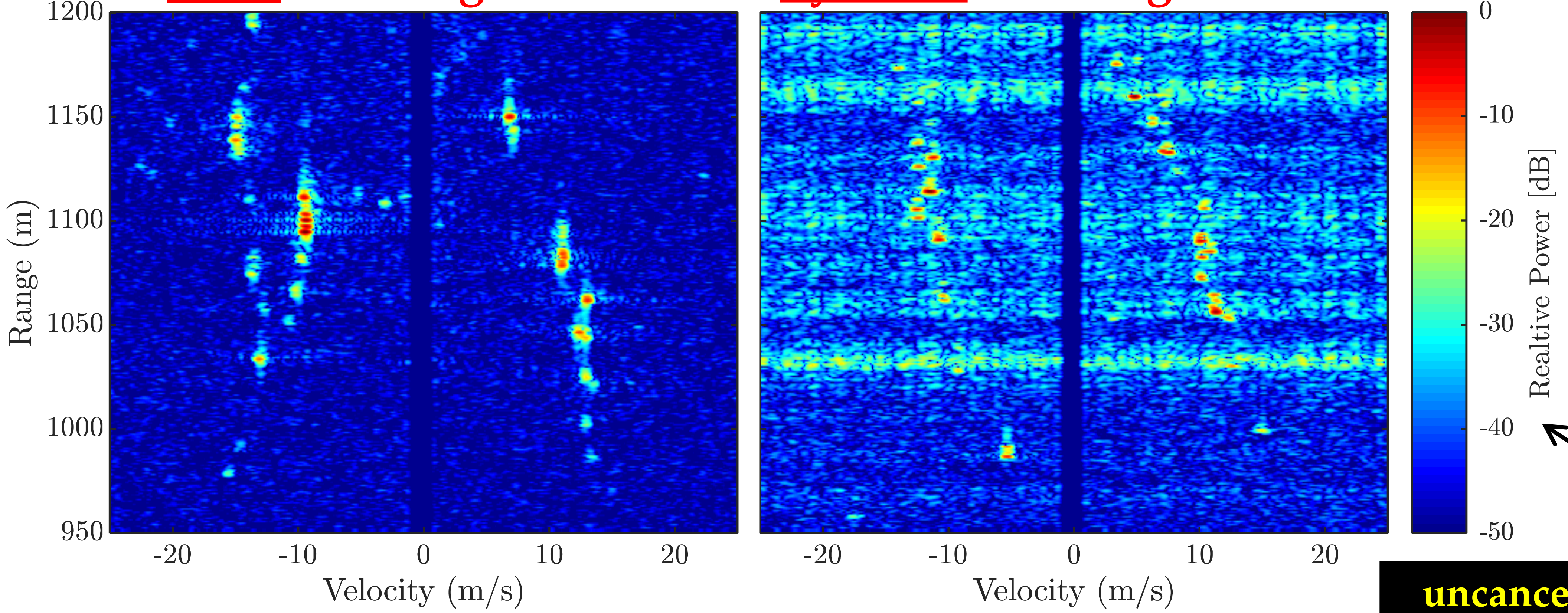
- However, nonrepeating waveforms cause **range sidelobe modulation (RSM) of clutter** when performing Doppler processing

- Because their spectral content can vary significantly during the CPI, the SAN and SAA methods realize ***additional residual clutter*** after clutter cancellation
  - Varying waveform spectra during the CPI induces a non-stationarity effect, inducing a **coupling of the range and slow-time Doppler domains**

Motivation

- Free-space measurements for MTI mode show that moving spectral notches to combat dynamic RFI (not included here) degrades clutter cancellation

static notching (no RFI)   dynamic notching (no RFI)

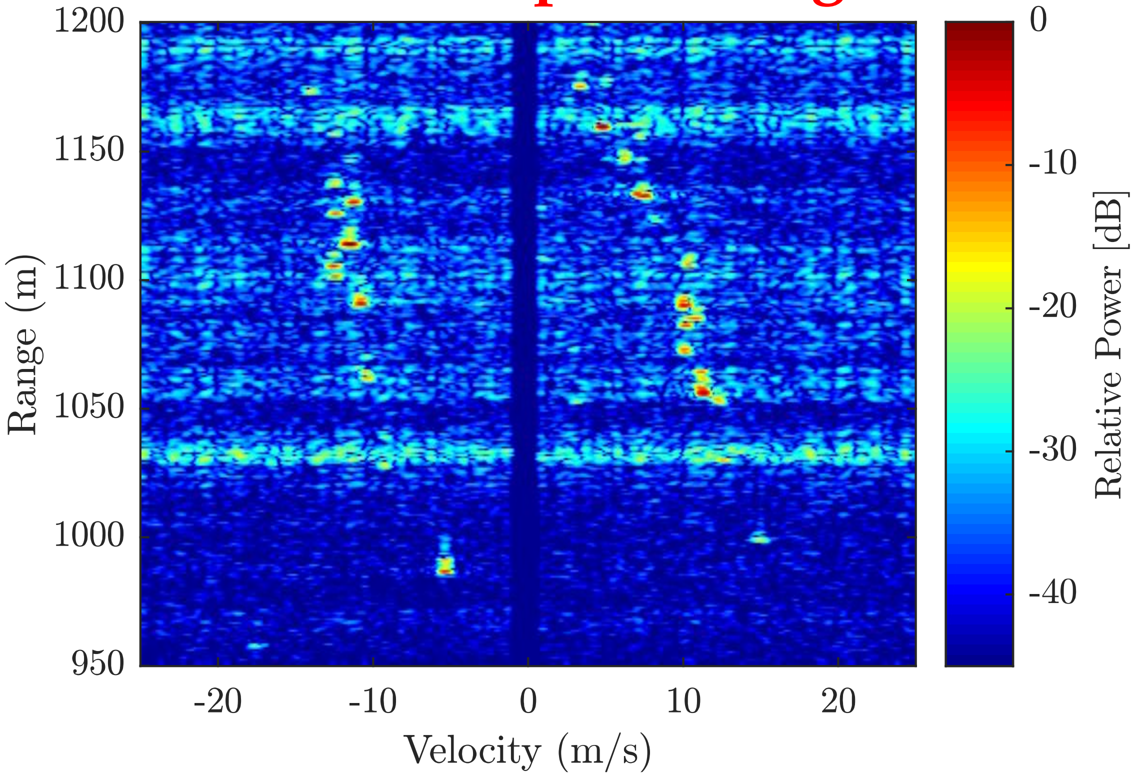


uncancelled clutter residue due to nonstationarity

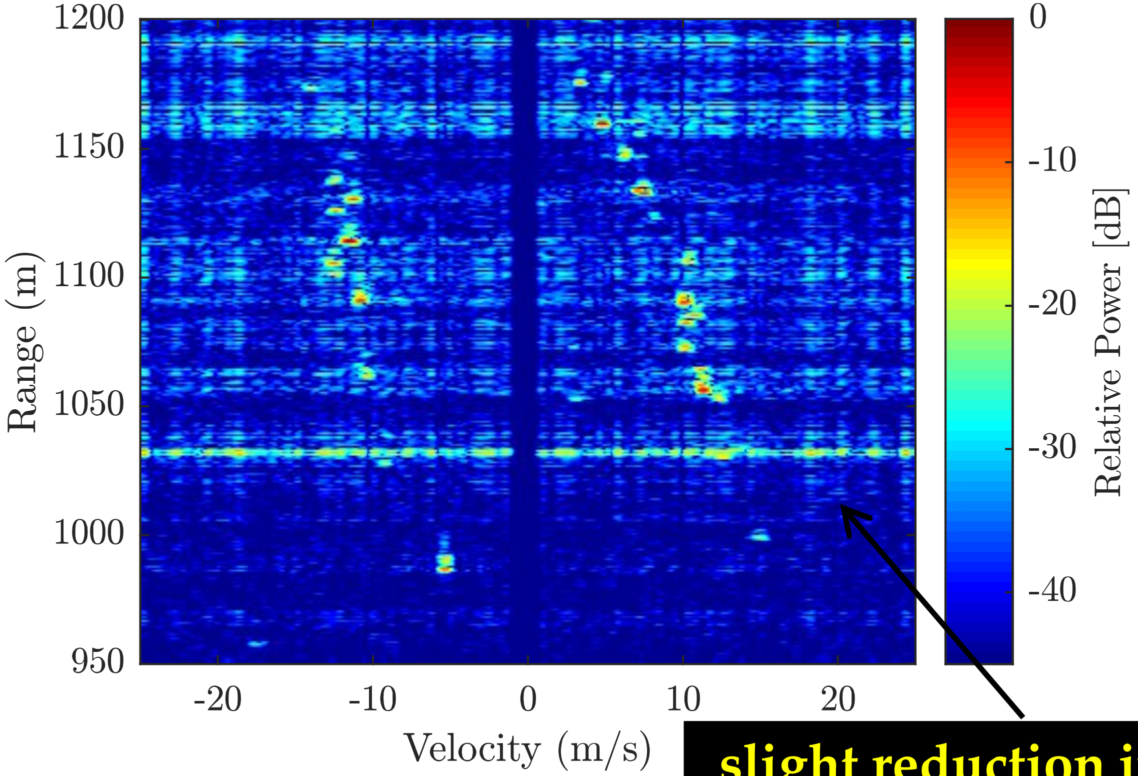
Motivation

- In **[4]** the optimal least-squares (LS) mismatched filer (MMF) was used to <u>partially reduce residual clutter</u> caused by dynamic spectral notching

Standard processing



LS-MMF



<u>slight</u> reduction in clutter smear

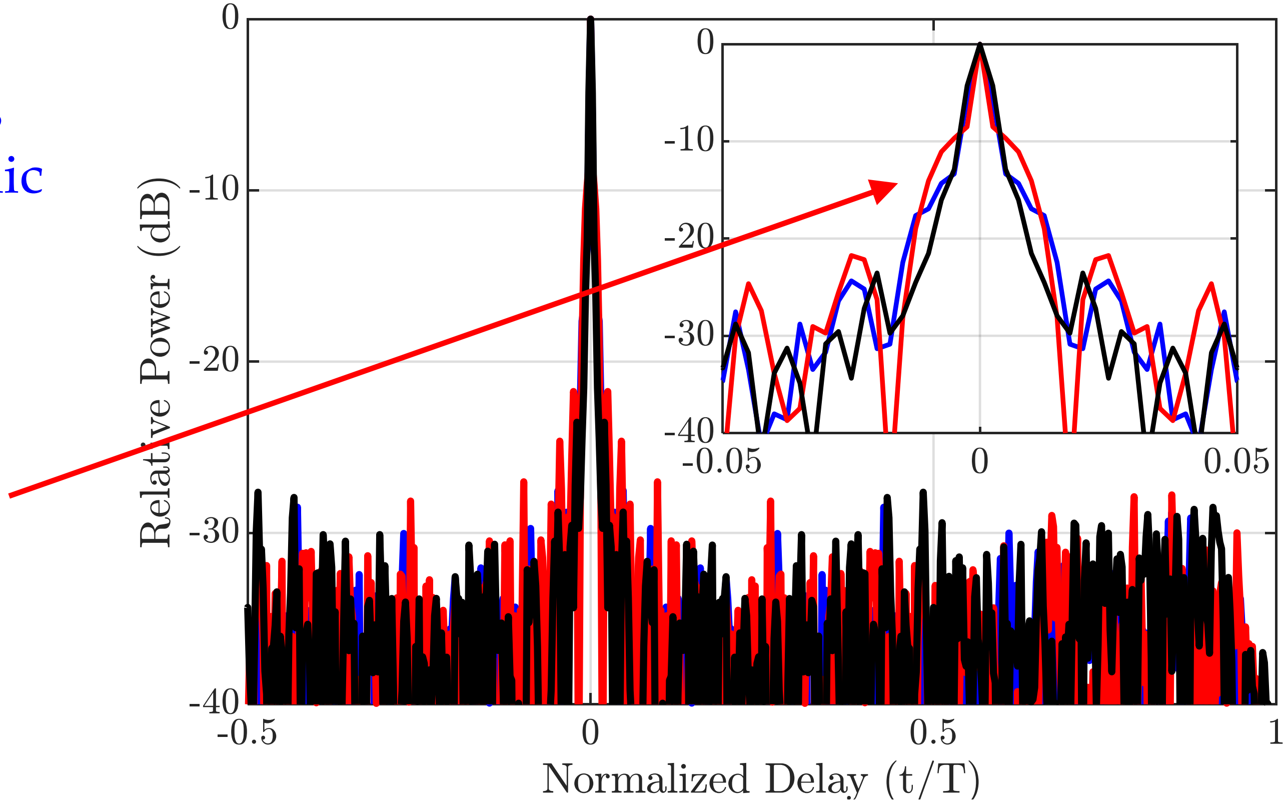
[4] B. Ravenscroft, et al, "Optimal mismatched filtering to address clutter spread from intra-CPI variation of spectral notches," *IEEE Radar Conf.*, Boston, MA, Apr. 2019.

Motivation

- Although the optimal LS-MMF provides a marginal reduction in clutter smearing, it is apparent that clutter smearing from dynamic waveform spectra is not mitigated by traditional filtering means

- It was determined that dynamic spectral notches induced a modulation of the pulse compression **mainlobe** in addition to RSM

- The degree of clutter smearing induced is commensurate with the degree of spectral change in the waveform CPI



Pulse compression responses of three different spectrally notched waveforms in a CPI (different notch widths and locations)

Motivation

- In [5], an ah hoc approach denoted as **De**void **C**lutter **C**apture **a**nd **F**illing (DeCCaF) greatly reduced clutter smear by homogenizing the clutter response across the CPI before Doppler processing
- Achieved by "borrowing" clutter from another compressed pulse response within the CPI to regain the clutter information missing from lost frequencies (due to spectral notching or changing LFM bandwidth/location)
- DeCCaF is computationally simple to implement, but can be limited by:
  - Lack of available pulses with the desired frequency content from which to borrow clutter
  - Loss of statistical independence during Doppler processing by repeating portions of the slow-time response

[5] J.W. Owen, et al, "Devoid clutter capture and filling (DeCCaF) to compensate for intra-CPI spectral notch variation," *SEE Intl. Radar Conf.*, Toulon, France, Sept. 2019.

Joint Domain Filtering

- Here we investigate joint range-Doppler processing to realize a multiplicative increase in degrees of processing freedom
  - Addresses the range-Doppler coupling effect caused by dynamically changing waveforms

- Specifically, the **Non-Identical Multiple Pulse Compression (NIMPC)** framework of **[6]** is applied to jointly perform:
  - Pulse compression
  - Doppler processing
  - Clutter cancellation

- NIMPC permits easy inclusion of clutter cancellation via max-SINR solution

[6] T. Higgins, et al, "Aspects of Non-identical multiple pulse compression," IEEE *Radar Conf.*, Kansas City, MO, May 2011.

Overview of NIMPC [6]

- Denote the reflected signal for all M pulses in the CPI corresponding to range cell ℓ as the row vector

$$\mathbf{y}(\ell) = \left[y_0(\ell) \;\; y_1(\ell) \;\; \cdots \;\; y_{M-1}(\ell) \right]$$

the mth element of which is

$$y_m(\ell) = \sum_{\theta} \left[\mathbf{x}_\theta^T(\ell)\, \mathbf{s}_m \; e^{jm\theta} \right] + n(\ell)$$

- The collection of N complex scattering coefficients (at Doppler phase shift θ) is

$$\mathbf{x}_\theta(\ell) = \left[x(\ell,\theta) \;\; x(\ell-1,\theta) \;\; \cdots \;\; x(\ell-N+1,\theta) \right]^T$$

- For time-bandwidth product BT, the length $N = K(BT)$ discretized waveform

$$\mathbf{s}_m = \left[s_{m,1} \;\; s_{m,2} \;\; \cdots \;\; s_{m,N} \right]$$

according to oversampling factor K (with respect to 3-dB bandwidth B), and $n(\ell)$ is complex white noise.

[6] T. Higgins, et al, "Aspects of Non-identical multiple pulse compression," IEEE *Radar Conf.*, Kansas City, MO, May 2011.

Overview of NIMPC [6]

- Now collect N contiguous fast-time samples of $\mathbf{y}(\ell)$ to construct the $N \times M$ matrix

$$\mathbf{Y}(\ell) = \sum_{\theta} \left[\mathbf{X}_{\theta}(\ell) \left(\mathbf{S} \odot \mathbf{V}_{\theta} \right) \right] + \mathbf{N}(\ell)$$

where

$$\mathbf{X}_{\theta}(\ell) = \begin{bmatrix} x(\ell,\theta) & x(\ell-1,\theta) & \cdots & x(\ell-N+1,\theta) \\ x(\ell+1,\theta) & x(\ell,\theta) & \cdots & x(\ell-N+2,\theta) \\ \vdots & \vdots & \ddots & \vdots \\ x(\ell+N-1,\theta) & x(\ell+N-2,\theta) & \cdots & x(\ell,\theta) \end{bmatrix}$$

$$\mathbf{S} = [\mathbf{s}_0 \ \mathbf{s}_1 \ \cdots \ \mathbf{s}_{M-1}]$$

$$\mathbf{V}_{\theta} = \mathbf{1}_{N\times 1} \left[1 \ e^{j\theta} \ \ e^{j2\theta} \ \ \cdots \ \ e^{j(M-1)\theta} \right]^T$$

$\mathbf{N}(\ell)$ is $N \times M$ complex white noise

[6] T. Higgins, et al, "Aspects of Non-identical multiple pulse compression," IEEE *Radar Conf.*, Kansas City, MO, May 2011.

Overview of NIMPC [6]

- Vectorizing $\mathbf{Y}(\ell)$ therefore yields the $NM \times 1$ vector

$$\tilde{\mathbf{y}}(\ell) = \text{vec}\{\mathbf{Y}(\ell)\} = \text{vec}\left\{\sum_{\theta}\left[\mathbf{X}_{\theta}(\ell)\left(\mathbf{S}\odot\mathbf{V}_{\theta}\right)\right]+\mathbf{N}(\ell)\right\}$$

- Based on the traditional maximum SINR solution, NIMPC then constructs a joint range-Doppler clutter cancellation filter as

$$\tilde{\mathbf{w}}_{\theta} = \left(\frac{\mu}{NM}\right)\mathbf{R}^{-1}\left[\text{vec}\{\mathbf{S}\odot\mathbf{V}_{\theta}\}\right]$$

where μ is an arbitrary scale factor and the diagonally-loaded, structured covariance is

$$\mathbf{R} = \mathbf{P}_{\phi}\,\mathbf{P}_{\phi}^{H} + \varepsilon\mathbf{I}$$

with $\mathbf{P}_{\phi}$ containing replicas of $\text{vec}\{\mathbf{S}\odot\mathbf{V}_{\theta}\}$ for values of $\phi=\theta$ associated with clutter Doppler, and also accounting for the possible delay shifts of each waveform.

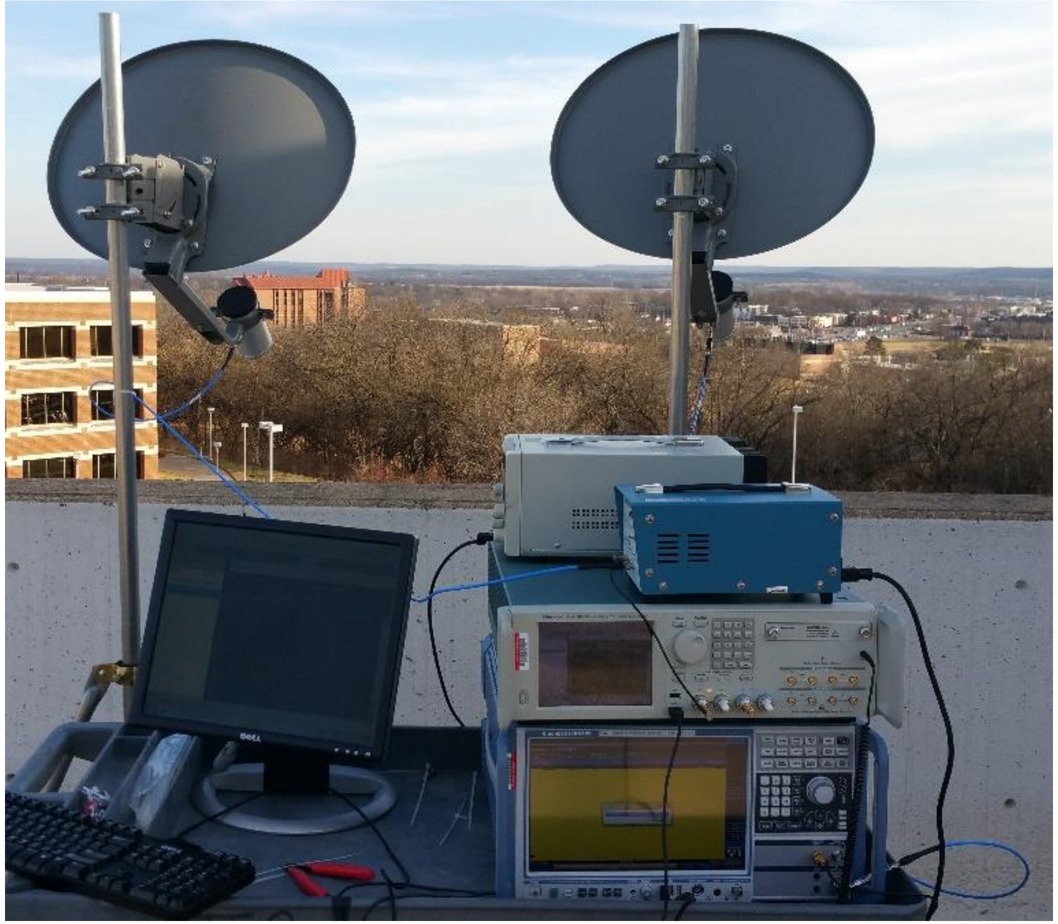
[6] T. Higgins, et al, "Aspects of Non-identical multiple pulse compression," IEEE *Radar Conf.*, Kansas City, MO, May 2011.

Experimental Assessment

- Free-space measurements were used to assess how well NIMPC can compensate for clutter RSM induced by dynamic waveform spectra
  - Collected from the roof of Nichols Hall on the KU campus illuminating moving cars/trucks traversing the intersection of 23rd & Iowa Streets in Lawrence, KS
  - CPIs of 125 unique SAA and SAN waveforms were transmitted back-to-back and the echoes captured ($BT = 200$, $K = 2$)
  - Hypothetical RFI (not included in measurement) changes after each pulse, necessitating a change in the spectral notch location for SAN and LFM location/bandwidth for SAA

- Range-Doppler response formed using 3 methods for both waveform CPIs
  - Standard pulse compression followed by standard Doppler processing with simple projection for clutter cancellation
  - Pulse compression with LS-MMF followed by clutter homogenization using DeCCaF, then standard Doppler processing and clutter projection
  - NIMPC, with structured covariance constructed from same Doppler as clutter projection

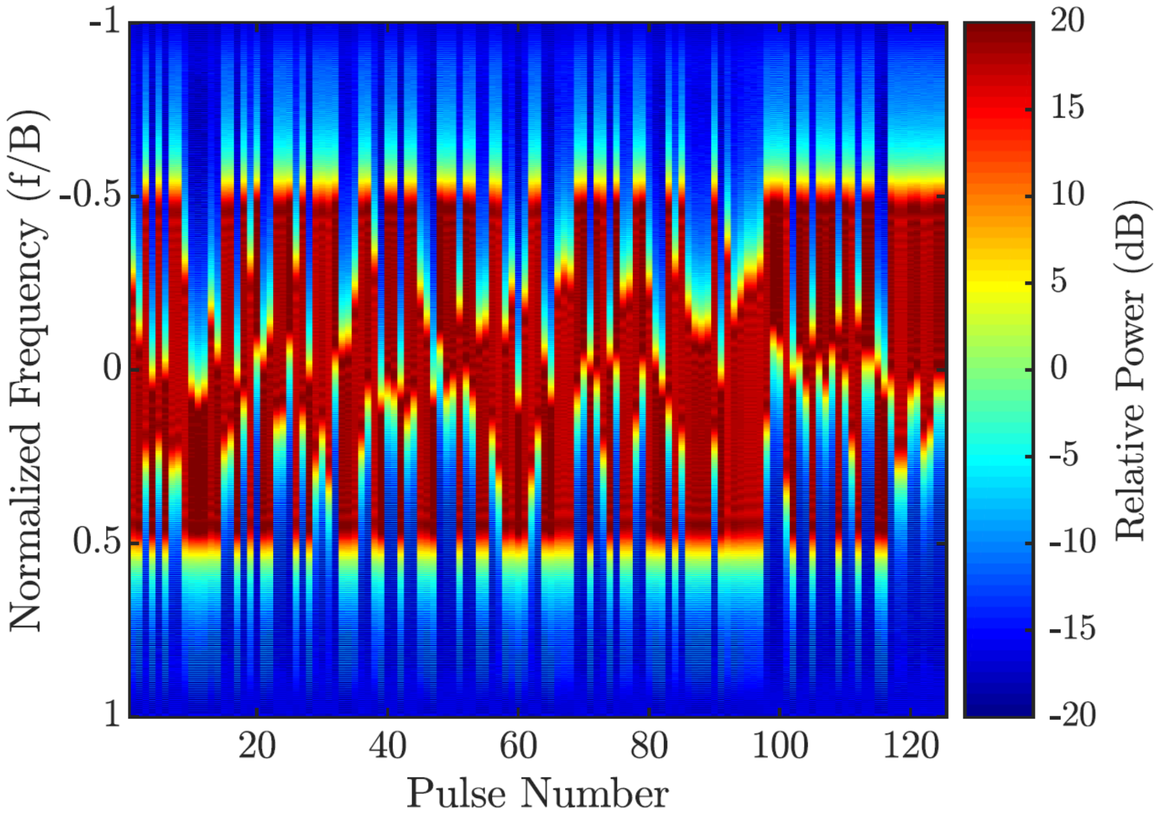
Experimental Assessment



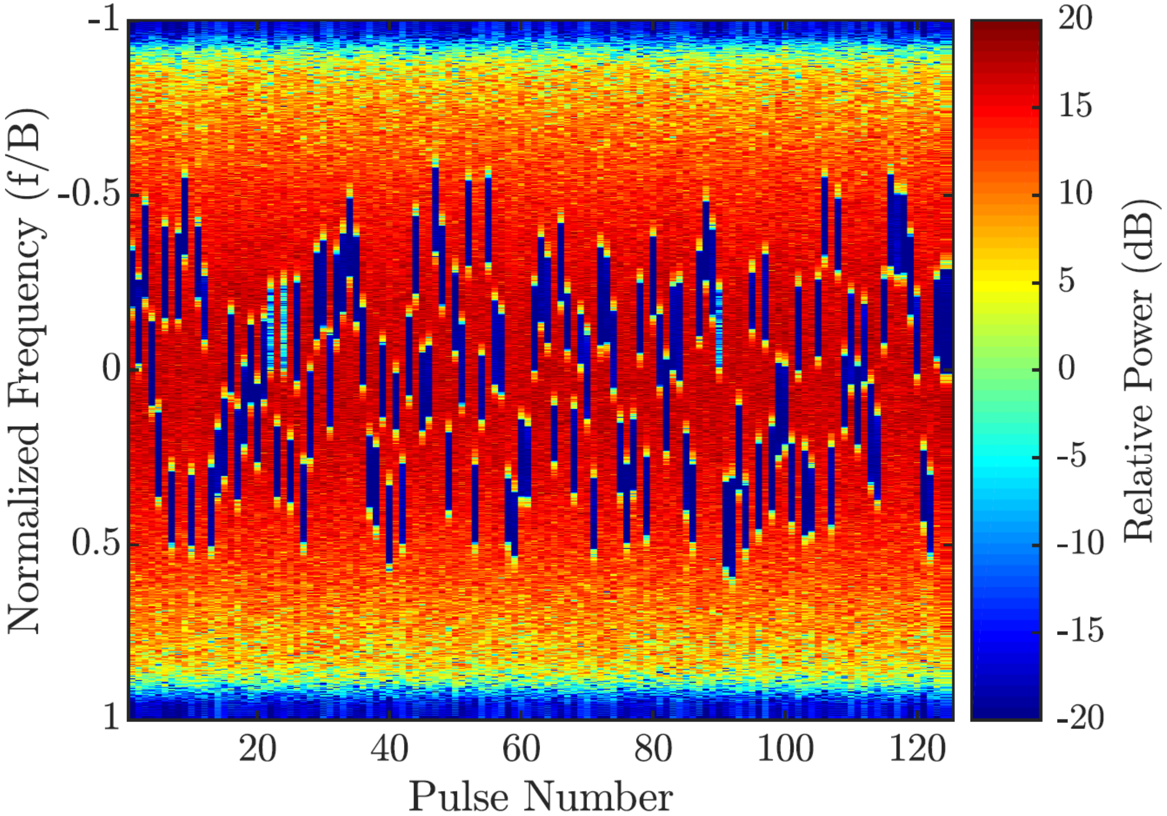
Test setup used to collect free-space measurements

Experimental Emission Spectra

Sense-and-avoid (SAA)

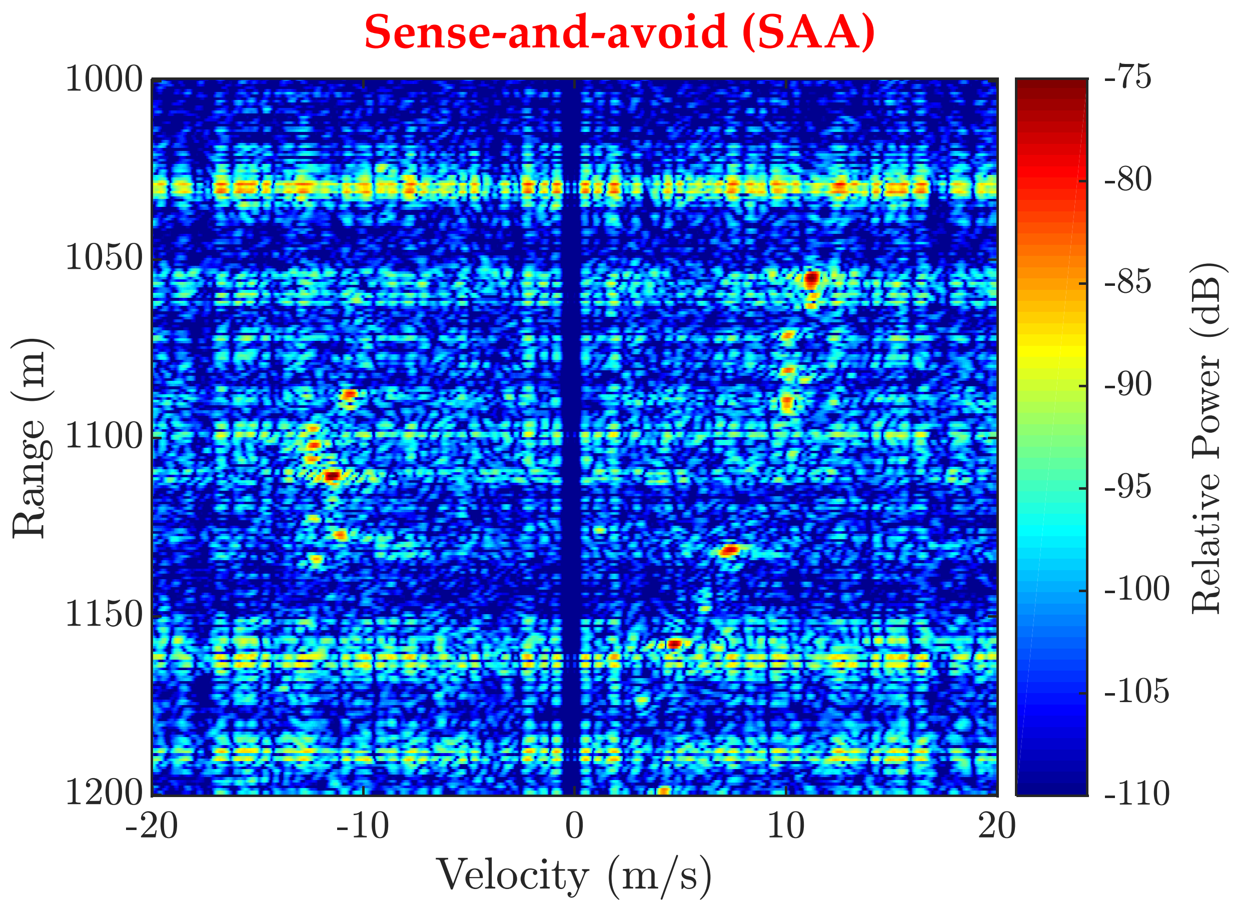


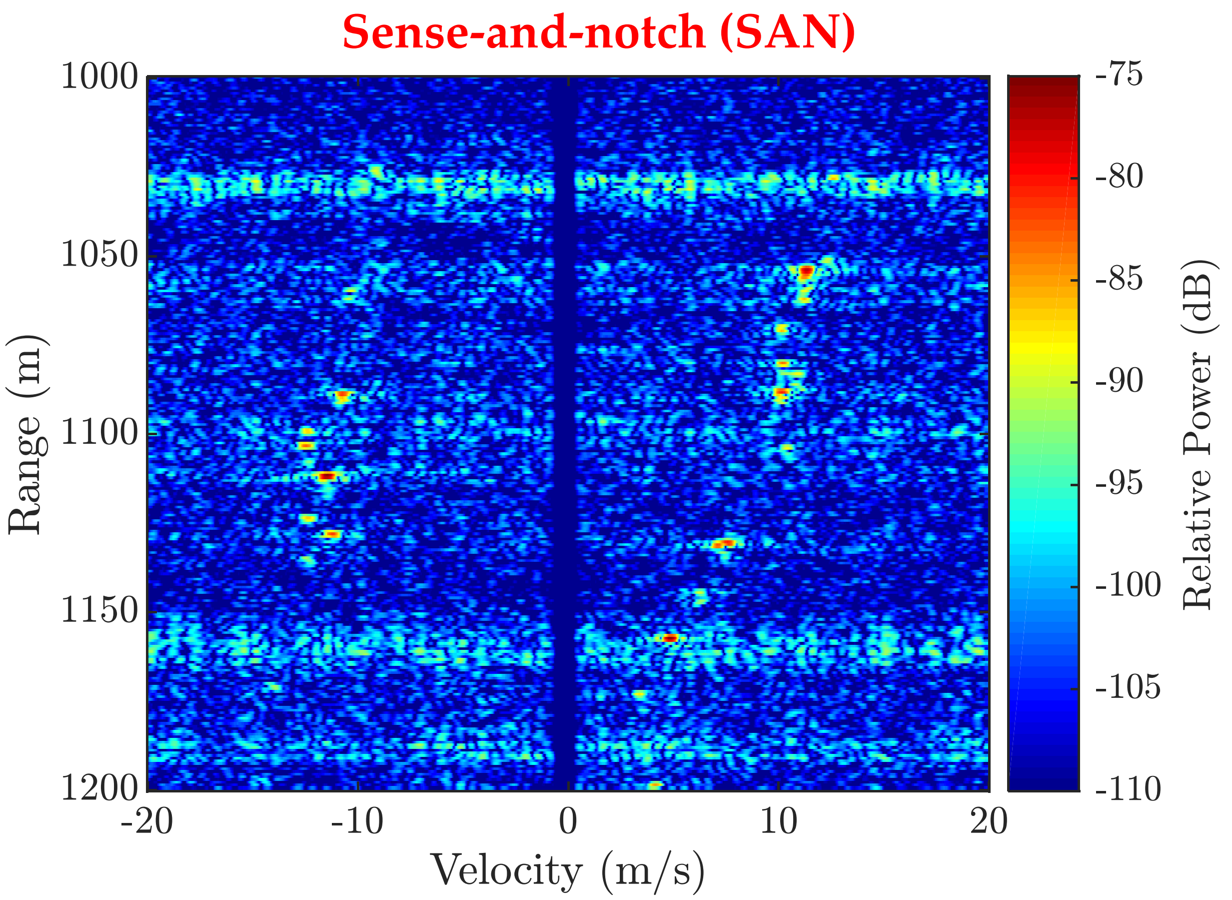
Sense-and-notch (SAN)



Loopback hardware captures of SAA and SAN waveform emission spectra used in experiment

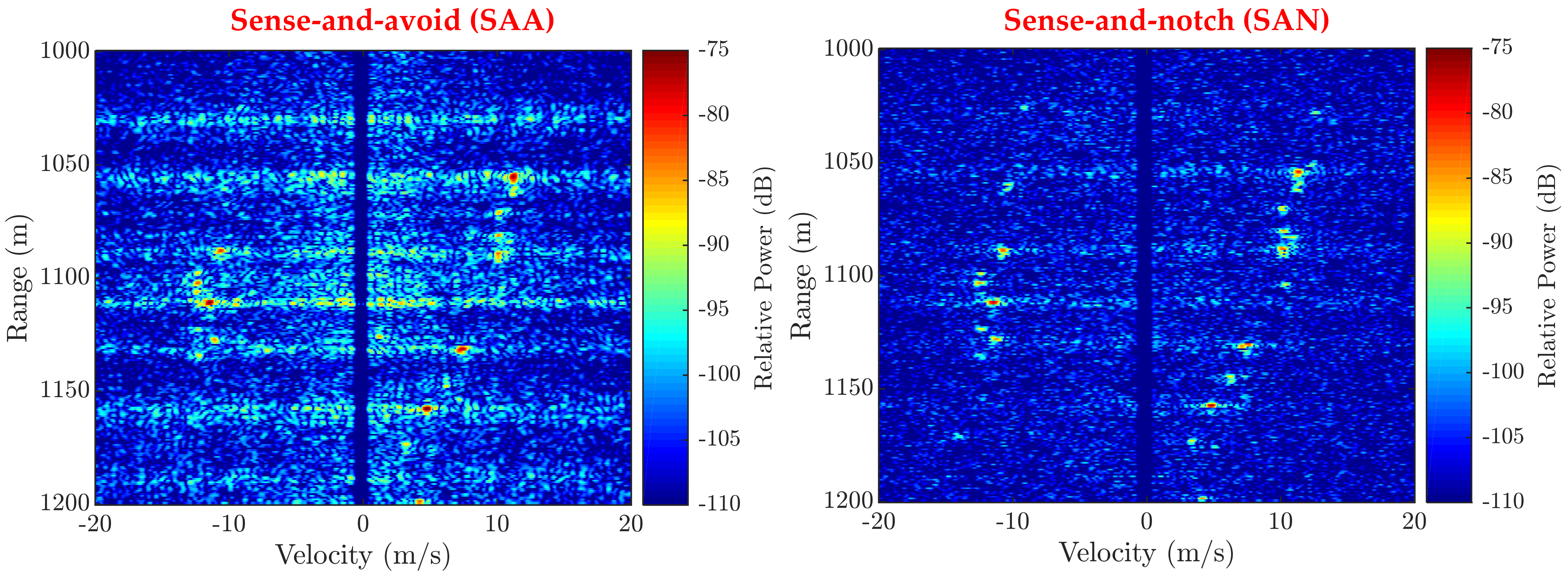
Experimental Results: Standard Processing





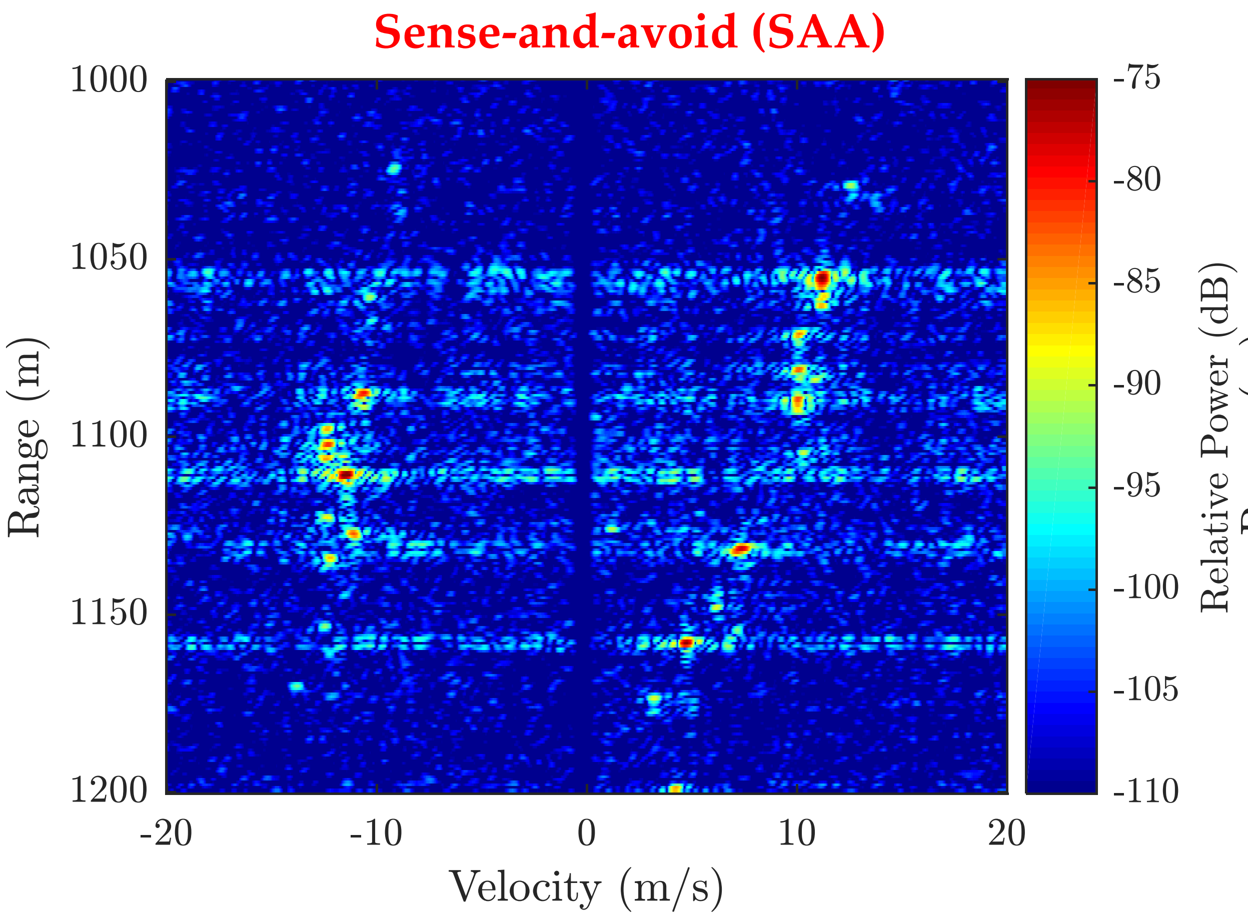
Range/Doppler clutter "streaking" is more pronounced in SAA (greater variation of spectral content) versus SAN

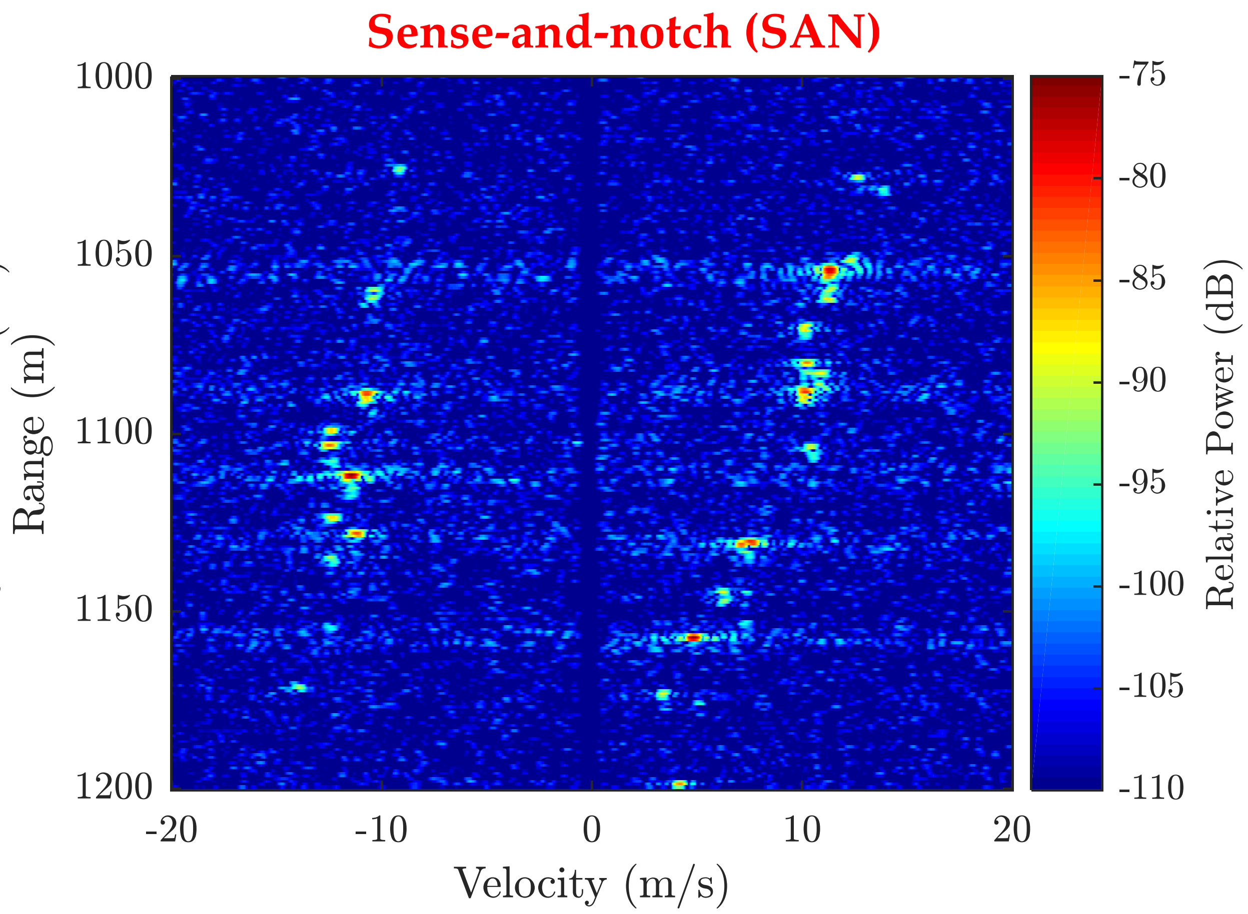
Experimental Results: LS-MMF + DeCCaF



LS-MMF + DeCCaF provides noticeable reduction in clutter smearing for both of these agile waveform sets

Experimental Results: NIMPC

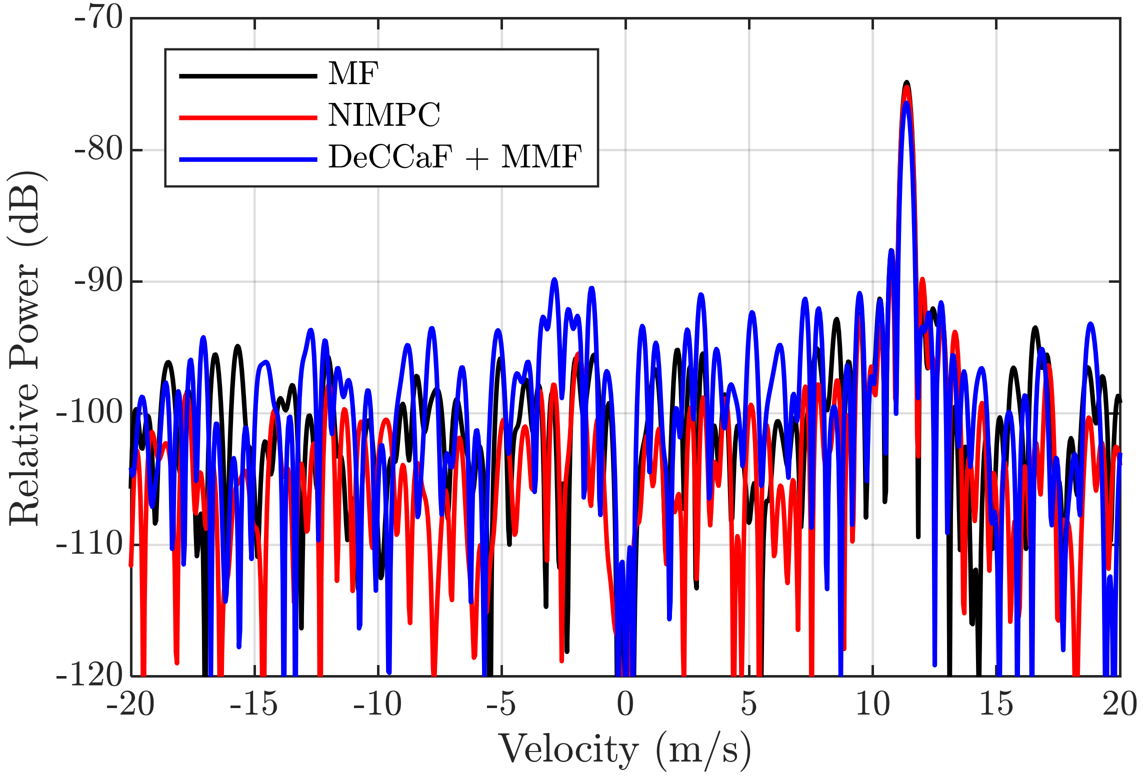




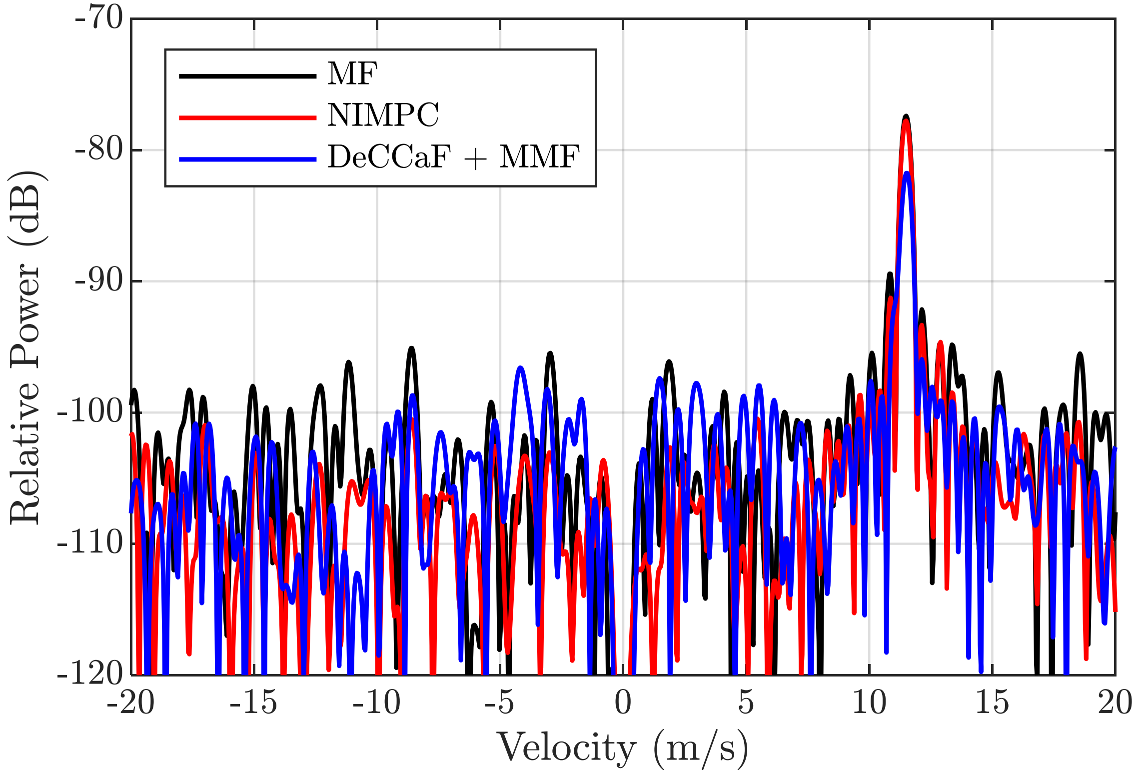
NIMPC provides significant reduction in clutter smearing along with reduction in background (noise + residual clutter) floor

Experimental Results: Single Doppler Slice

Sense-and-avoid (SAA)



Sense-and-notch (SAN)



Single Doppler slice at range of 1055 m: NIMPC has lowest background AND very little SNR loss. Implies better downstream detection performance.

Conclusions

- Agile waveforms provide promising capabilities to address in-band RFI for cognitive radar in emerging spectrum sharing paradigms
  - But they introduce clutter modulation effects due to inherent range-Doppler coupling
- Similar to how STAP addresses angle-Doppler coupling of clutter for airborne GMTI, joint range-Doppler coupled processing can do likewise for agile waveforms (as exemplified by NIMPC)
- It should be noted that NIMPC incurs a large computational & memory cost
  - Inversion of a large covariance matrix ($NM \times NM$ = 50,000 × 50,000 for the data shown)
  - Storage and multiplication of large matrices
- More computationally feasible solutions to joint-domain processing are currently being investigated