Signal Sensing, Design and Delivery for Electronic Warfare

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WP 1.2: Signal Subspace Validation

Content

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- Context of the challenge
- Time-Frequency domain processing
- Hybrid Hough Transform Method
- Hardware Exploitation Paths
- Worked Examples
- Conclusions

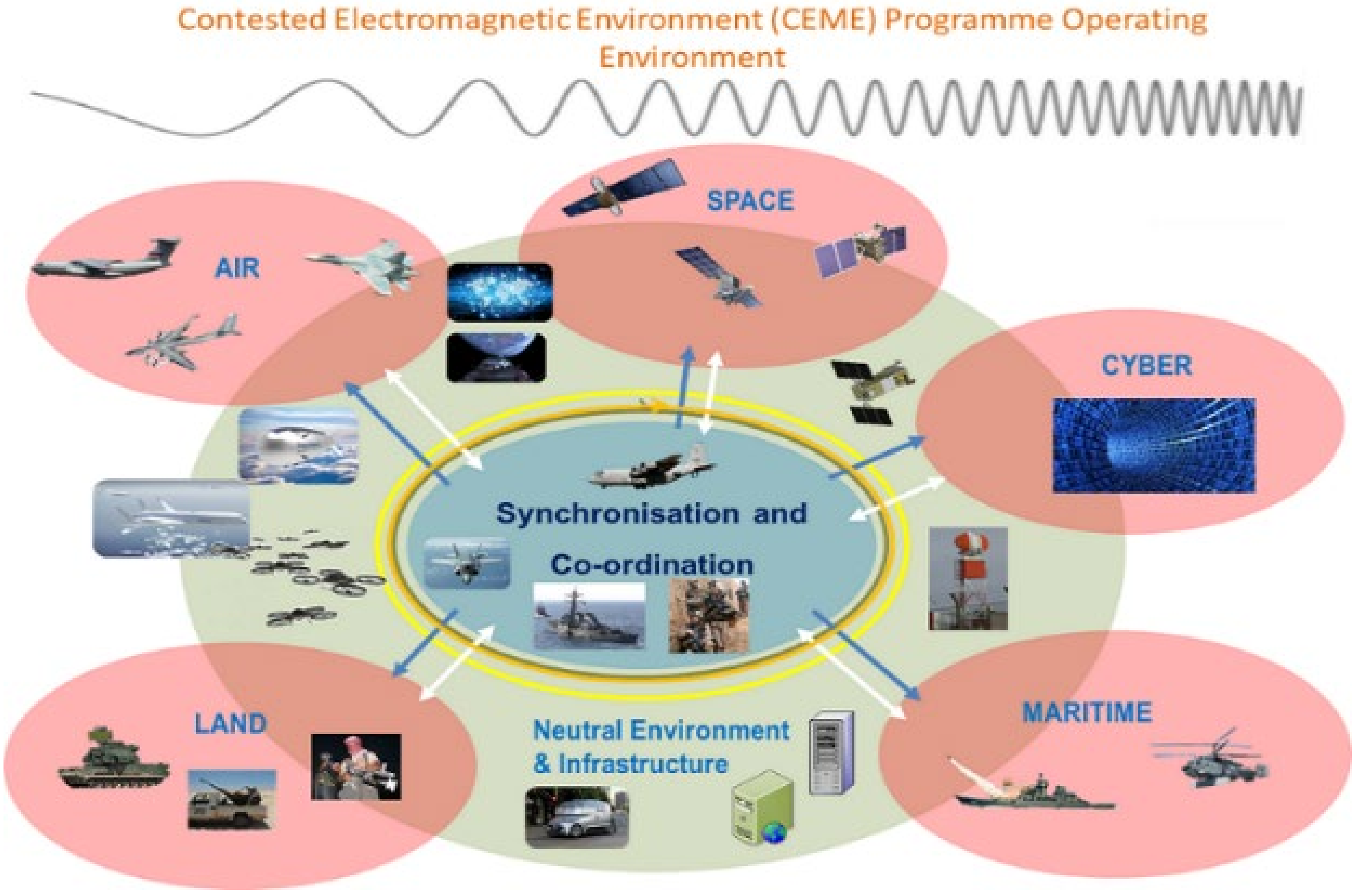
WP 1.2 Objectives

This WP aims to investigate innovative signal subspace processing to both detect LPI waveforms to enable high classification success rates on their properties:

- These properties are labelled the waveform Pulse Descriptor Words (PDW)
- A key goal is to both detect the signals present and autonomously extract PDWs from these signals.
- The use of bilinear time-frequency transforms such as Wigner-Hough and Wigner-Hough-Radon transforms that have shown to be successful against LPI FMCW signatures feature extraction even at low SNR values [Gulum:2012].
- We will focus will be on exploiting the cross terms generated by these transforms and operating this signal processing in parallelized way, with multiple transforms, in order to maximize the ability to classify actual signals that are present.
- Optional: Experimentally validate concepts with real RF receivers

T. O. Gulum, A. Y. Erdogan, T. Yildirim and P. E. Pace, "A parameter extraction technique for FMCW radar signals using Wigner-Hough-Radon transform," 2012 IEEE Radar Conference, Atlanta, GA, 2012, pp. 0847-0852.

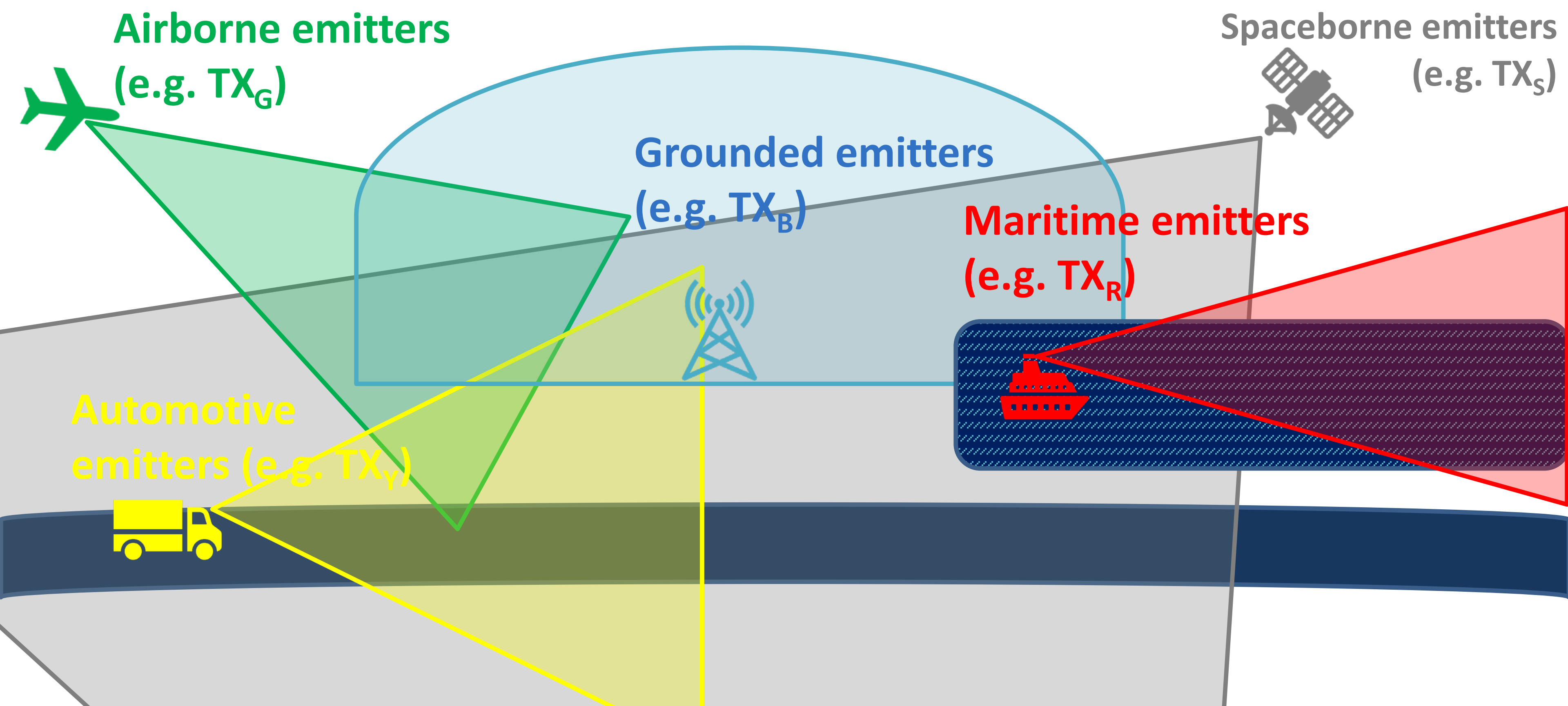
Context of problem



Defence and Security Accelerator (DASA), "The Invisible Battlespace" GOV.UK. https://www.gov.uk/government/publications/competitionthe-invisible-battlespace/competition-document-the-invisiblebattlespace (accessed Oct. 31, 2019)

Context of problem

Increasing…Number of emitter



Context of problem

Increasing…Complexity of RF transmitter

Historically

Radar would have

- Single frequency
- Always use the same waveform
- Fixed or small subset of PRFs
- Mechanically steered
- Fixed beam pattern

Current and Future Systems

- Wideband transmitters
- Multi-frequency bands simultaneously being used
- Dynamically designed waveforms
- Totally dynamic PRF
- AESA antennas with rapidly changing beam pattern

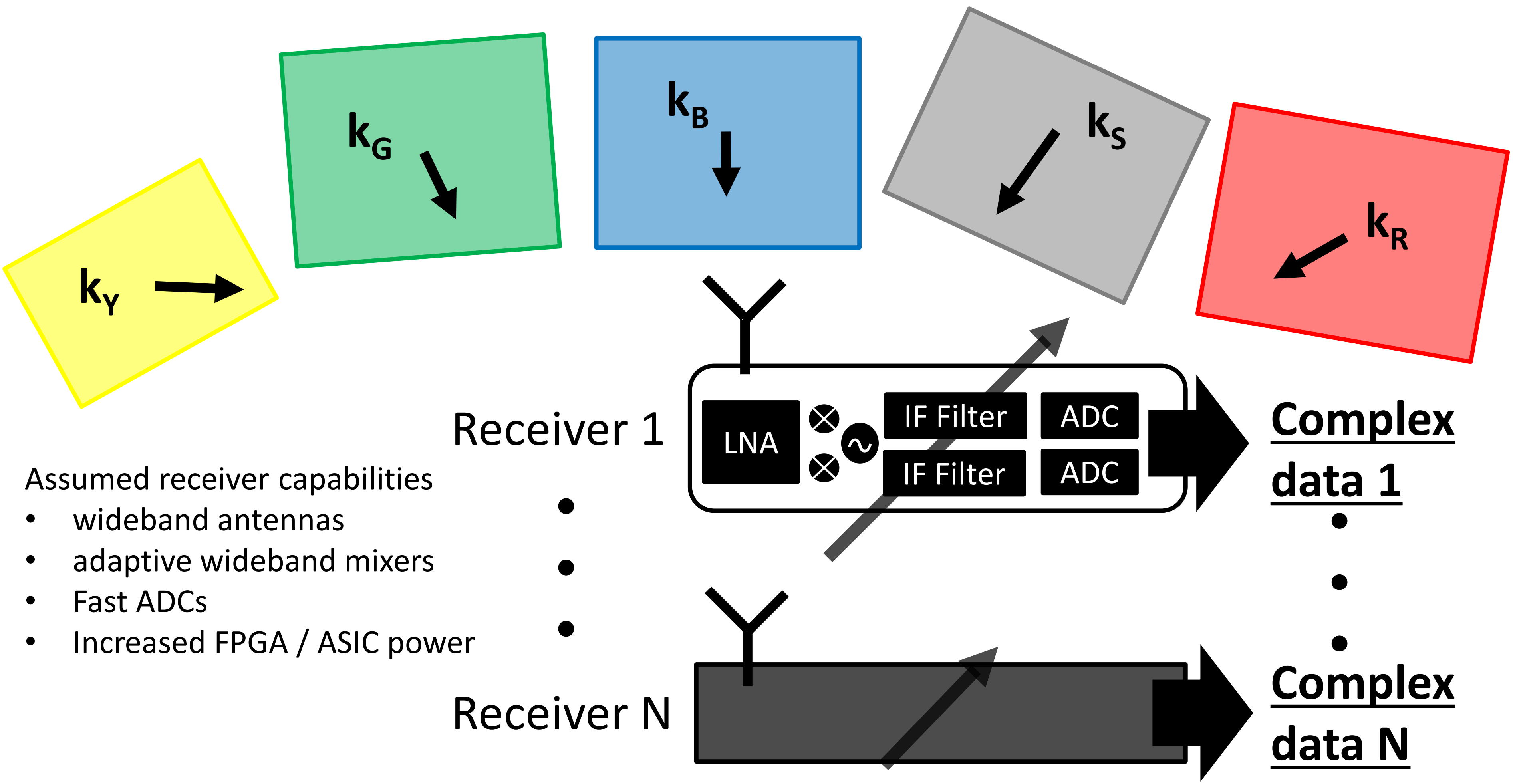
Context of problem

- Difficulties:
  - Challenging Low Probability of Intercept (LPI) waveforms now common
  - Congested / Dynamic Environment
  - Complex radar waveforms exist such as coded and staggered
  - Interleaving signals due to multiple transceivers or strong multipath
- Waveform classification requirements
  - Low SNR capability
  - Accurate waveform parameter estimation
  - Robust to waveform parameter variations

All these facts make the surveillance and extraction of information from EM signals more and more challenging!

Building a solution

- Fortunately most of the technological advancements used in modern RF emitters are transferable to receivers



Assumed receiver capabilities

- wideband antennas
- adaptive wideband mixers
- Fast ADCs
- Increased FPGA / ASIC power

PDW & Waveform Definitions

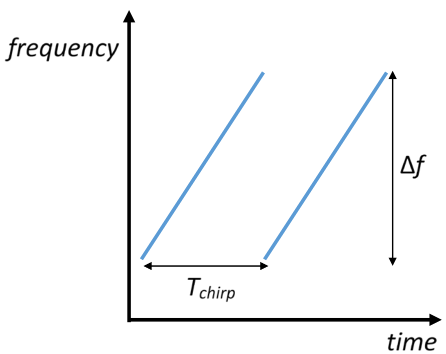
- Scenario of a single transmitter and a single ES receiver aiming to detect/classify waveform parameters
- Waveform defined as:

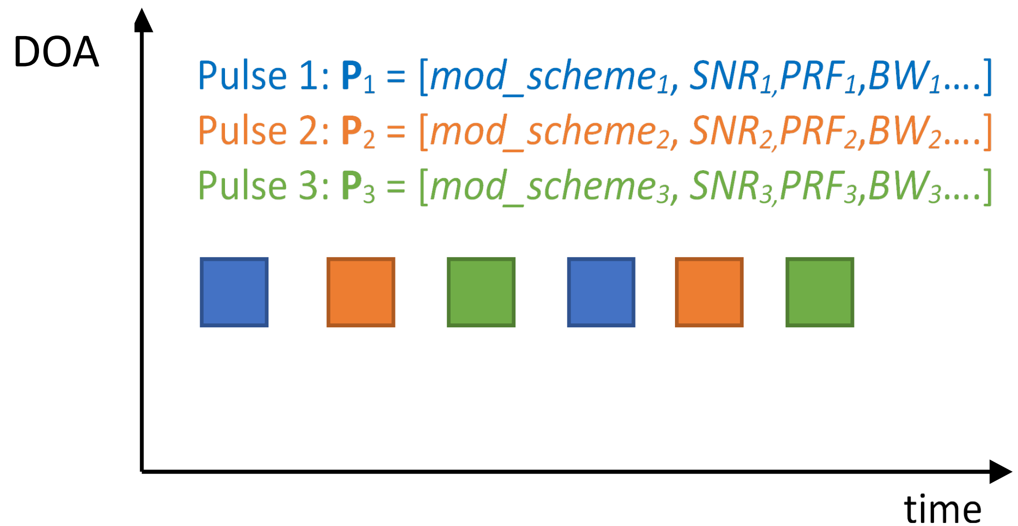
$$s(t) = A\, e^{j(2\pi(K)t^2+\varphi)} + AWGN(\mu_n = 0, \sigma_n)$$

$$\text{for } 0<t<\Delta T$$

$$\text{where } K = \Delta F/\Delta T$$

- Amplitude *A*, Chirp bandwidth Δ*F*, and Chirp duration Δ*T* that is contaminated with Additive White Gaussian Noise (AWGN) with zero-mean and a variance of σ_n is given by
- Extracted PDW are:
  - $PDW = [\Delta f_e, \Delta T_e, SNR_e]$





B. Willetts, M. Ritchie, H. Griffiths,"*Optimal Time-Frequency Distribution Selection for LPI Radar Pulse Classification*", IEEE RadarCon 2020, Washington D.C.

TF transforms

- **Gabor Transform (GT)**
  - Short time Frequency Transform (STFT) is given by
  - $\Phi_G(\theta,\tau) = \int h^*\left(u-\frac{\tau}{2}\right)h\left(u+\frac{\tau}{2}\right)e^{-j\theta u}du$ Eqn (1)
  - This is the Gabor transform when used with a Gaussian window
  - It is limited by the resolution of the window imposed by the windowing function h(.)

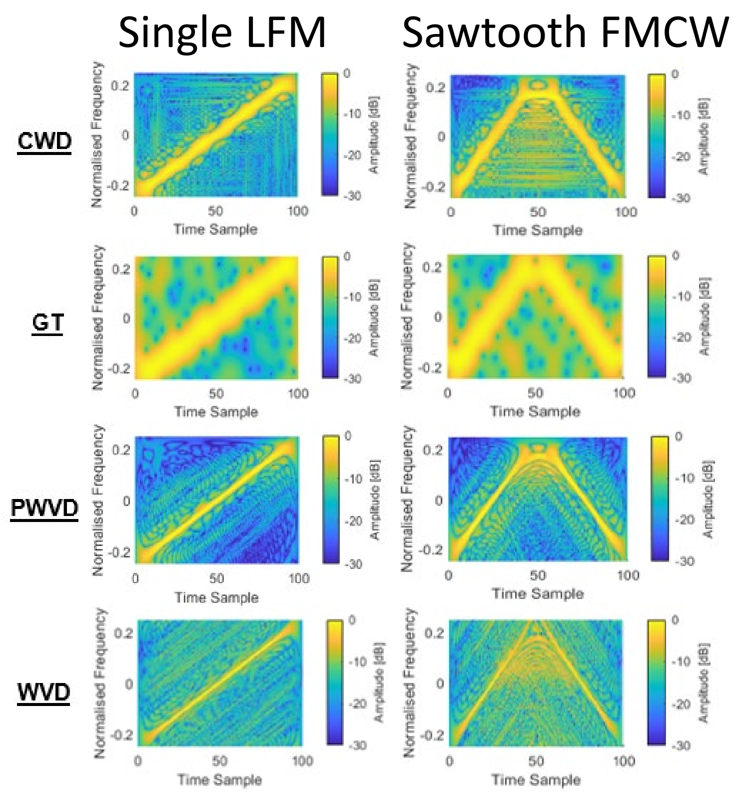
- **Wigner-Ville Distribution (WVD)** is the FT of the autocorrelation function which is the Cohen class expression Eqn(2) with a unity kernel function Eqn (3):
  - $C(t,f) = \int s\left(\theta+\frac{\tau}{2}\right)s^*\left(\theta-\frac{\tau}{2}\right)\phi(t-\theta,\tau)e^{-j2\pi f\tau}d\theta d\tau$ Eqn (2)
  - $\Phi_{WV}(\theta,\tau) = 1$ Eqn(3)

- **Pseudo Wigner-Ville Distribution**
  - This uses the above **WVD** with an additional Gaussian smoothing function.

- **Choi-Williams Distribution (CWD)**
  - This has a kernel function that gives it a better resolution than the **GT** and less cross-term interference than the **WVD**.
  - It is calculated with Eqn (2) while using the kernel function below
  - $\Phi_{CW}(\theta,\tau) = e^{-\alpha(\theta\tau)^2}$ Eqn (4)

Comparison of TF Transforms

- Choi-Williams (CWD)
- Gabor Transform (GT)
- Pseudo WVD (PWVD)
- Wigner-Ville (WVD)

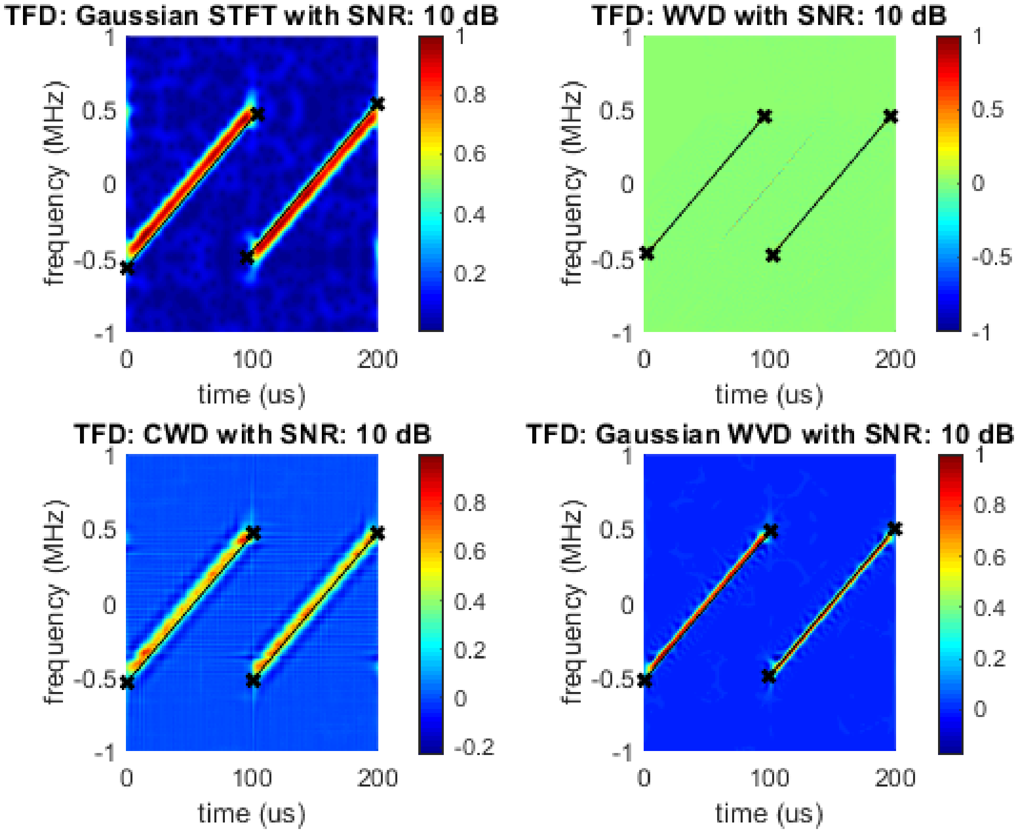


Noisy LFM data (SNR=10dB, Δ*f*=0.5*Fs* and Δ*T*=100/*Fs*) processed using different TF methods: (a) GT (b) WVD (c) PWVD (d) CWD

Can qualitatively see that the resolution, SNR are varying significantly across these different TF transform outputs

Comparison of TF Transforms

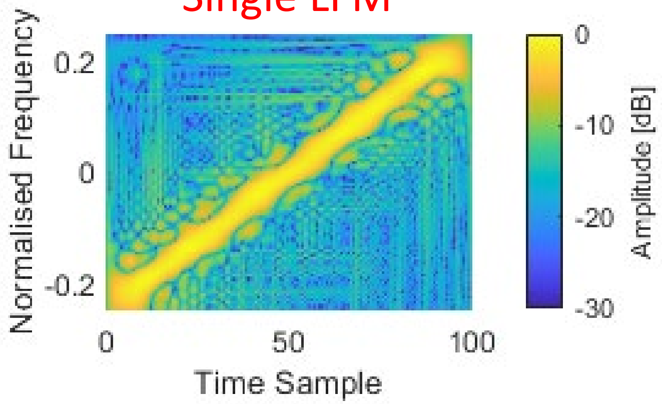
- Pair of chirps shown
- Clear difference in the resolution, SNR and cross term affects depending on TF used
- Cross terms generated. These will be reviewed later

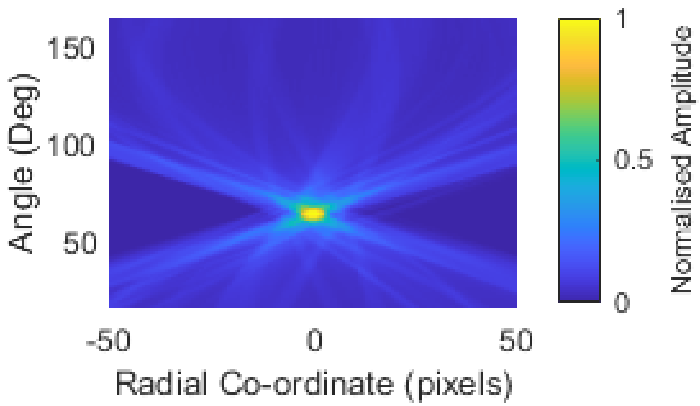


Hough Transform

- Hough/Radon Transforms allow a summation of analytical geometries such as lines, ellipses and circles
- Should be applied in the domain that the feature is detectable with the largest extent
- The Hough transform has relatively low complexity to extract lines
- Well-suited for intercepting signals that posses linear frequency modulation

Single LFM

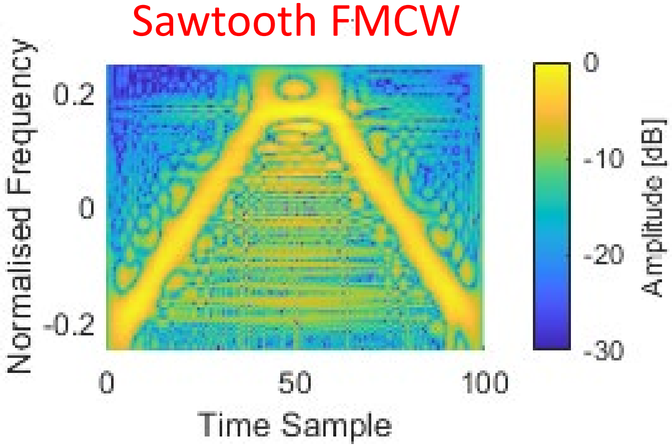


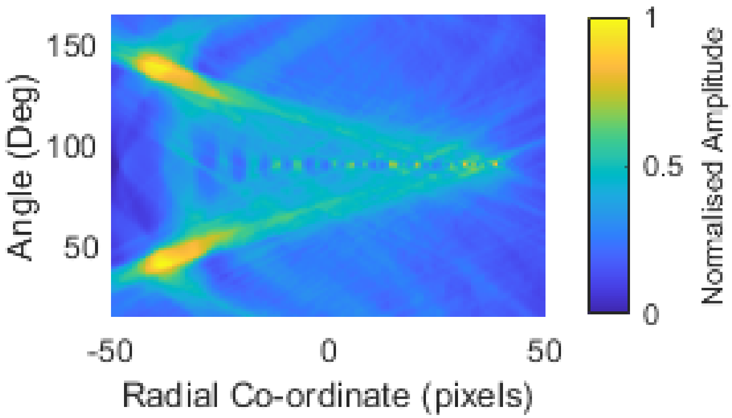


B. Boashash, *Time-Frequency Signal Analysis and Processing - A Comprehensive Reference*. Elsevier, 2016.

Hough Transform

- Image processing techniques can be used to extract the waveform parameters in a quantitative form
- The Hough Transform can be used to compress the linear LFM signatures into a single point of energy.
- The Hough transform has relatively low complexity to extract lines
- Well-suited for intercepting signals that posses linear frequency modulation

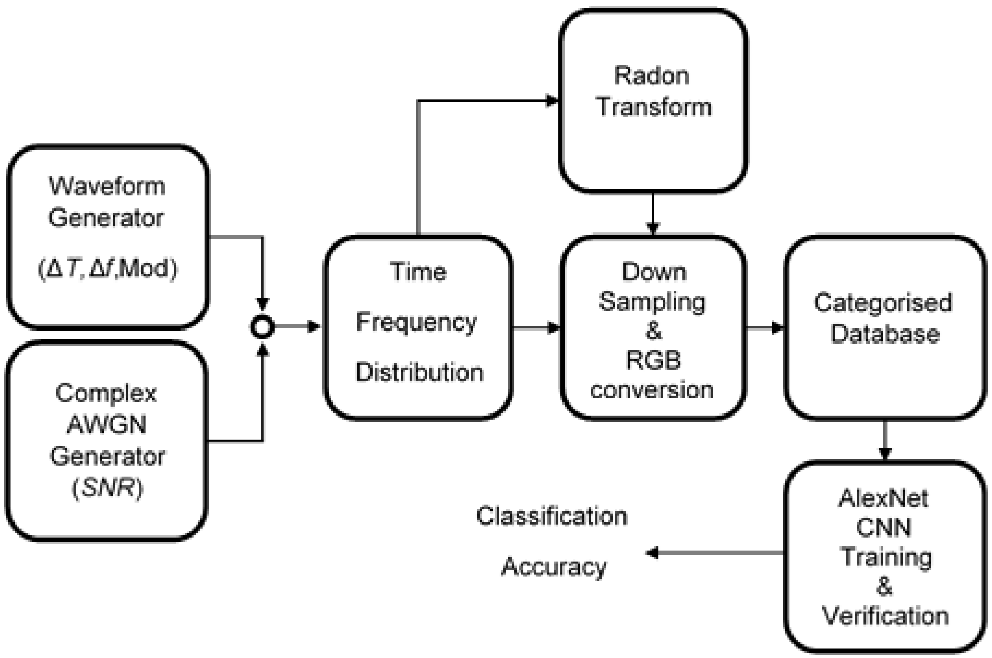




B. Boashash, *Time-Frequency Signal Analysis and Processing - A Comprehensive Reference*. Elsevier, 2016.

Classification Process

- Results generated for IEEE 2020 RadarCon publication
- Based on AlexNet which is a Convolution Neural Network (CNN)
- Flow of the classification of signals



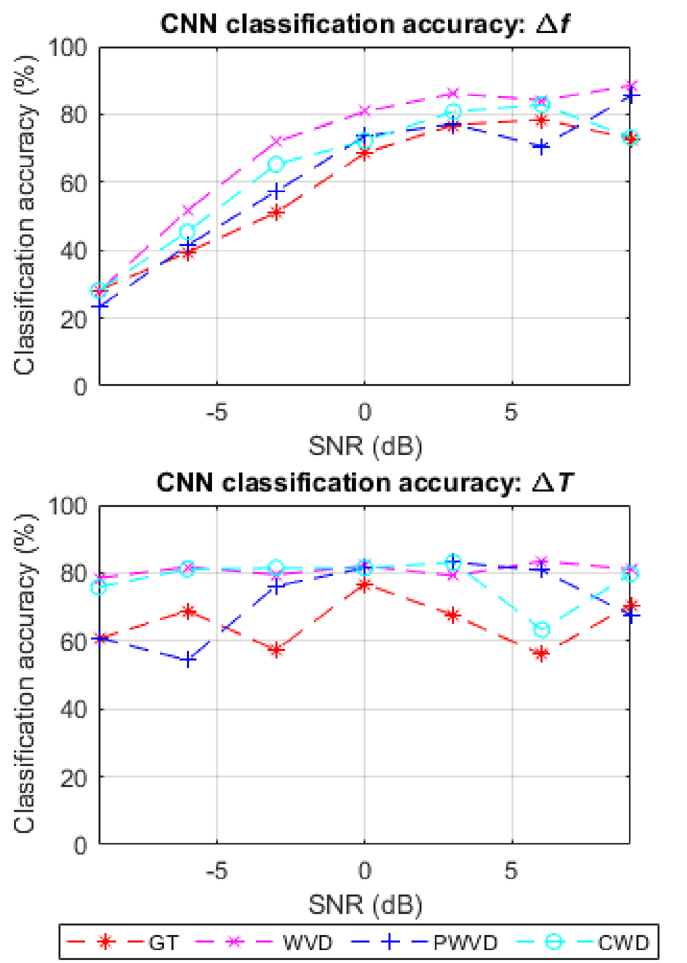
Classification Results

- Varied SNR from -9 to +9 dB used 1000 Monte Carlo repeats per SNR.
- The bandwidth was less accurately estimated than Chirp Period at lower SNRs but more accurately estimated at higher SNRs
- WVD found to be the most effective in majority of cases

SNR	Δf_s	ΔT_s	$(\Delta f_s + \Delta T_s)/2$
-9 dB	28%	78%	53%
-6 dB	52%	82%	67%
-3 dB	72%	81%	76%
0 dB	81%	82%	81%
3 dB	86%	83%	83%
6 dB	84%	83%	84%
9 dB	88%	81%	85%

Optimal TFD color scheme

GT		PWVD	
WVD		CWD	



Robustness to Noise

- Also tested variants of Hough-Wigner transforms

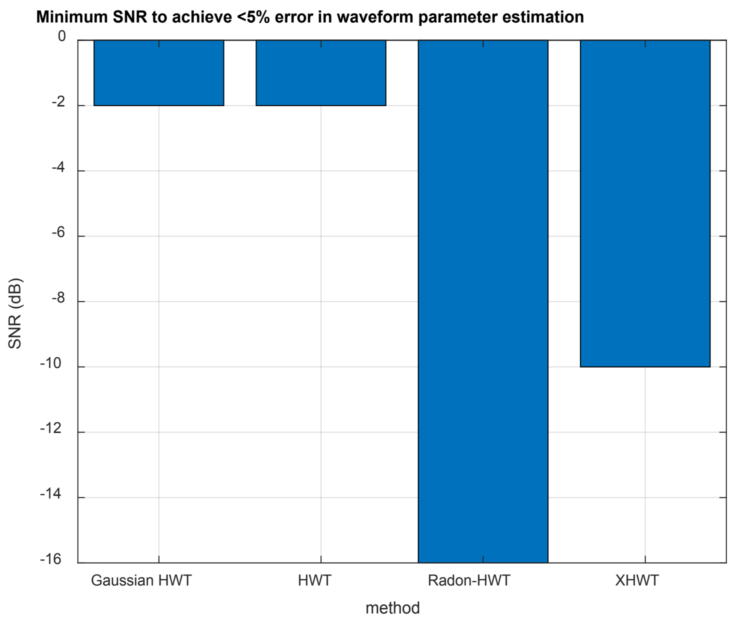
Hough-Wigner Transform (HWT)

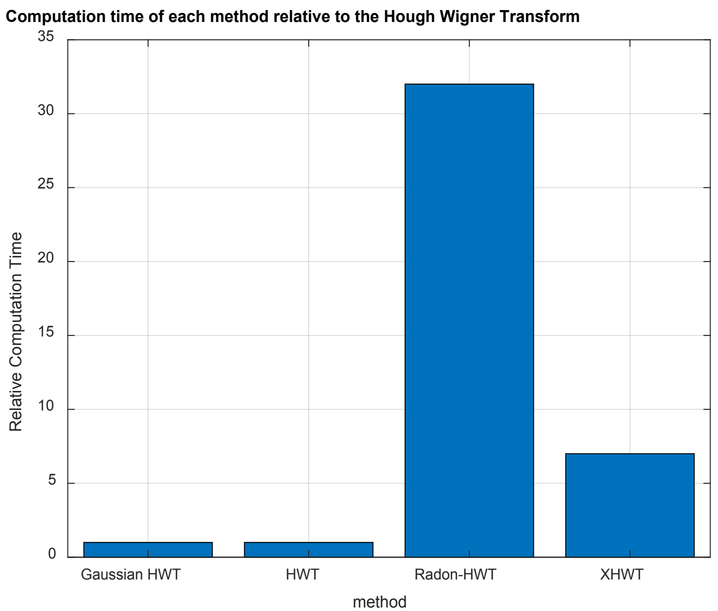
Gaussian-windowed HWT

Radon-Hough-Wigner Transform (RHWT)

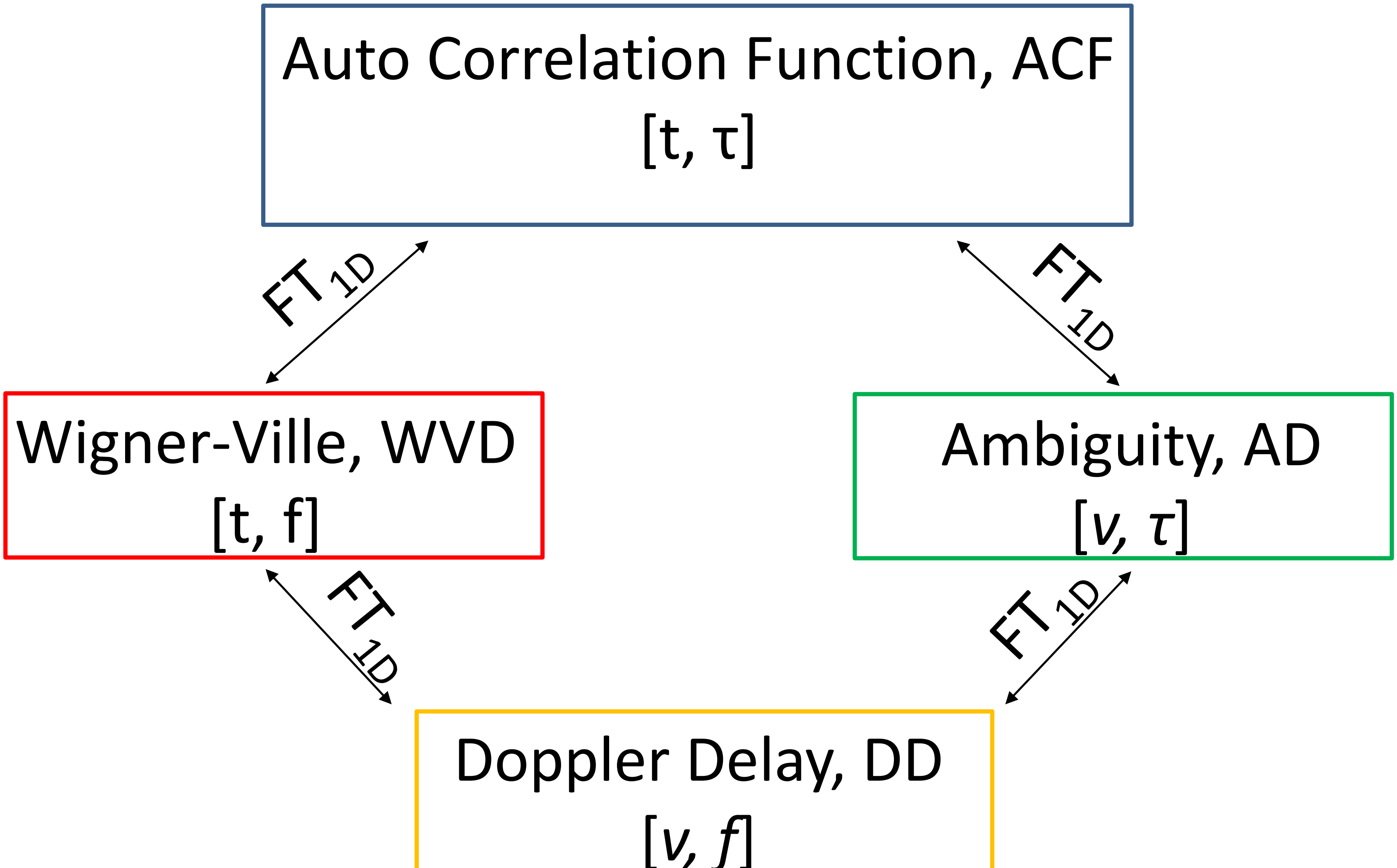
Cross-term Hough Wigner Transform (XHWT)

- Radon HWT showed to be most resilient but required longest computation time.





Signal Domains



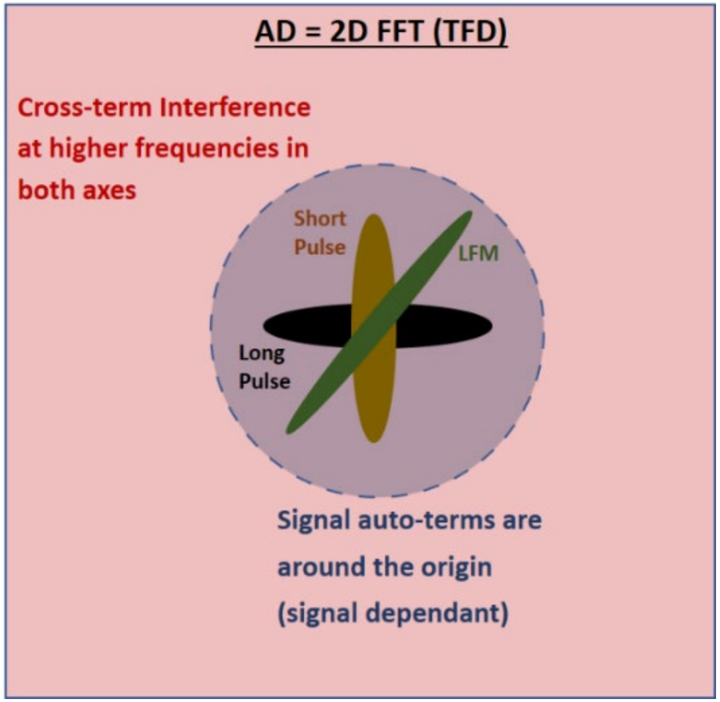
Ambiguity Domain
Auto-terms + Cross Terms

Below images shows the auto-term signatures produced by three different modulation types (LFM, CW/long-pulse and impulse/short-pulse) in the AD over an observation period.

The signatures within the AD representation that exist at the same locations as the physical signal are called the Auto-Terms (AT) components.

Cross-Term (CT) interference also exist when intercepting multiple pulses due to inter-products present within the QTF transform

CT interference is often deemed undesirable and thus kernels have been designed and used to suppress it [1] [2]

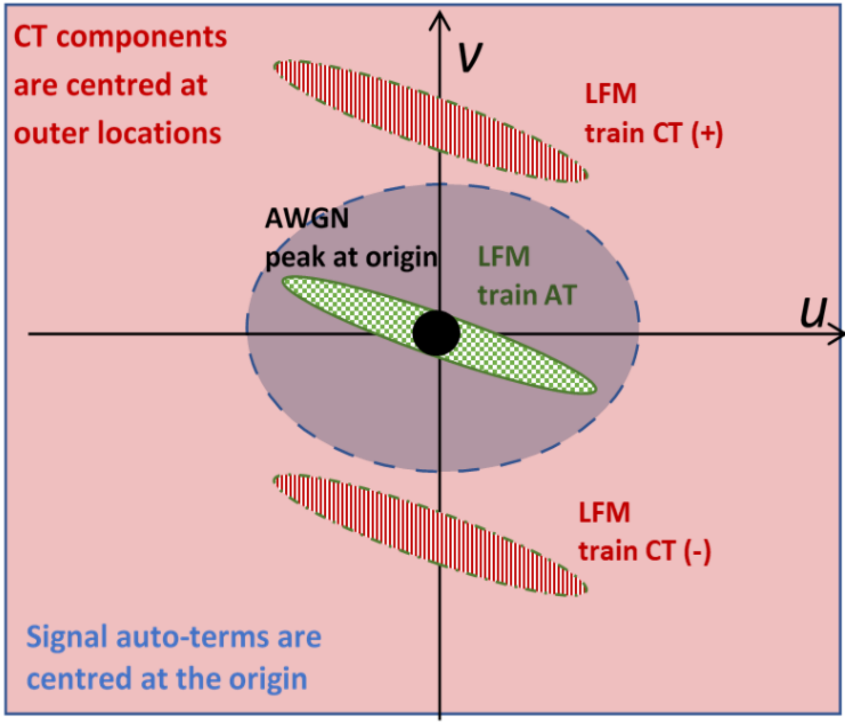


[1] H.-I. Choi and W. J. Williams, 'Improved time-frequency representation of multicomponent signals using exponential kernels', *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 37, no. 6, pp. 862–871, Jun. 1989, doi: 10.1109/ASSP.1989.28057.
[2] Y. Zhao, L. E. Atlas, and R. J. Marks, 'The use of cone-shaped kernels for generalized time-frequency representations of nonstationary signals', *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 38, no. 7, pp. 1084–1091, Jul. 1990, doi: 10.1109/29.57537.

Ambiguity Domain
Auto-terms + Cross Terms

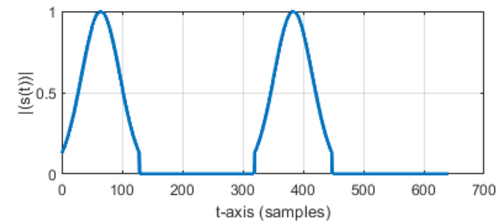
Below images shows the auto-term signatures produced by three different modulation types (LFM, CW/long-pulse and impulse/short-pulse) in the AD over an observation period.

- Different modulation schemes will have different geometries present in both the TFD and AD.
- Emitters that make use of signals that are narrow-band at each time instance will have linear features for pulsed CW, LFM and traditional phase-coded modulations.
- NLFM as well as more elaborate modulation schemes and/or emitters may exhibit non-linear features in the TFD and AD

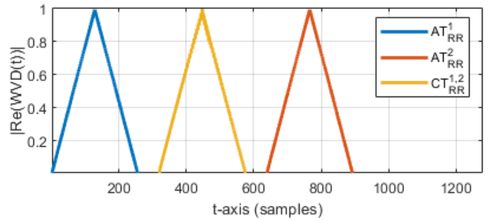


Ambiguity Domain
Auto-terms + Cross Terms

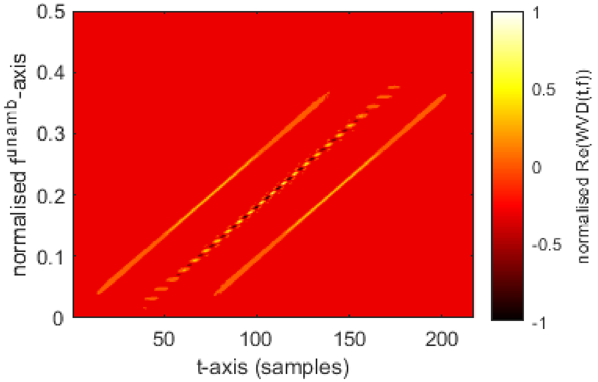
- Top Figure shows 2 Tx pulses with Gaussian weightings



- Middle Figure shows the WVD envelope is shown below this has both CT and ATs



- Bottom figure shows the WVD representation for a pair of Gaussian windowed LFM pulses



Auto-Terms / Cross-Terms

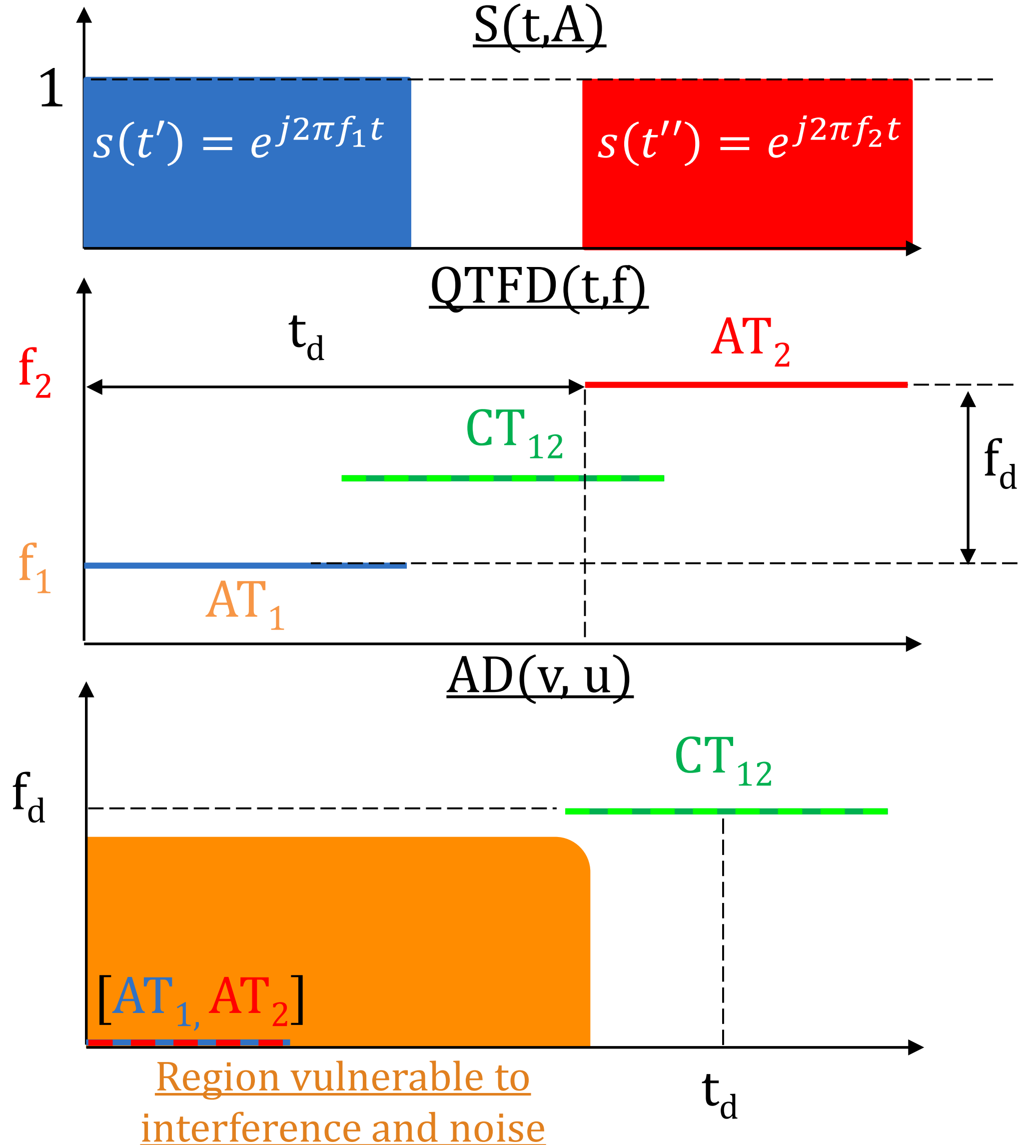
- Quadratic Time-Frequency (QTF) analysis of complex data allows Pulse Descriptor Words (PDWs) to be obtained in a subspace that is robust to interference and noise

$$PDW = [TOA, fc, \Delta F, \Delta T, A, \dots]$$

- Oscillatory Cross-Term (CT) signatures are located at outer-regions of the Ambiguity Domain

$$AD(u,v) = \mathcal{F}_{2D}(QTFD(t,f))$$

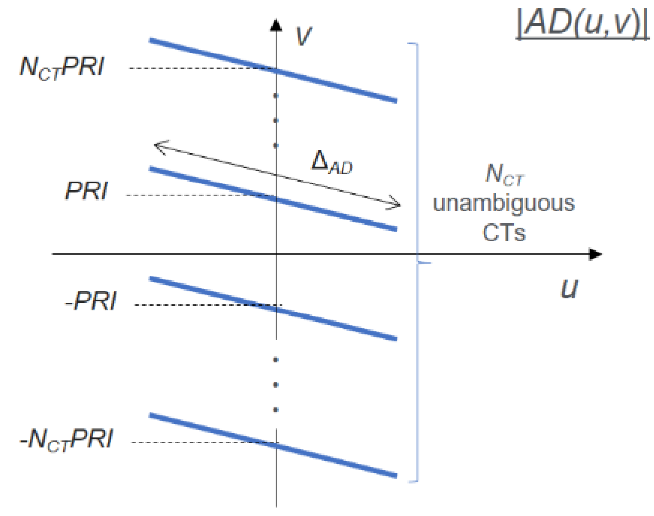
- Leverage CT to extract PDW from regions unaffected by noise/interference
  - Concept of radar waveform design to place CT in specific regions

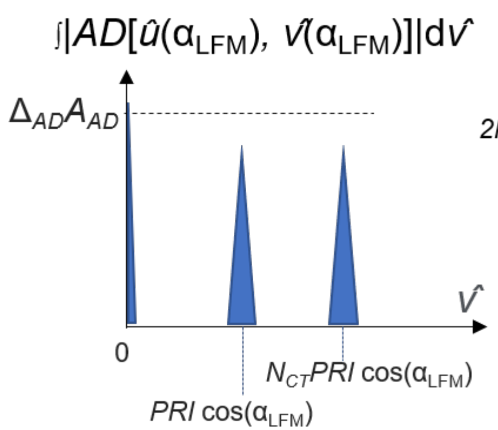


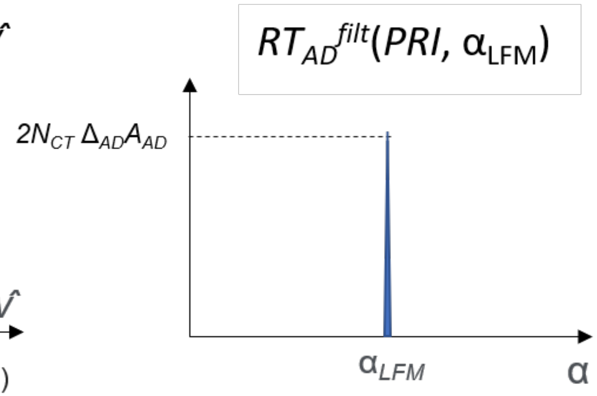
Exploitation of CTs

1. Generate series of waveforms
2. Generate AD signatures
3. Use shearlet dictionary for sparse representations
   A. Ensures only waveforms of a given type are input to RT
4. Use Radon Transform (RT) to focus energy
5. Extract PRI and BW PDWs

More info on technique within publication







B Willetts, M. Ritchie, H. Griffiths, "Novel method for assigning pulse descriptor words to radar signals in a complex electromagnetic environment", Submitted to IET RSN, Oct 2020.

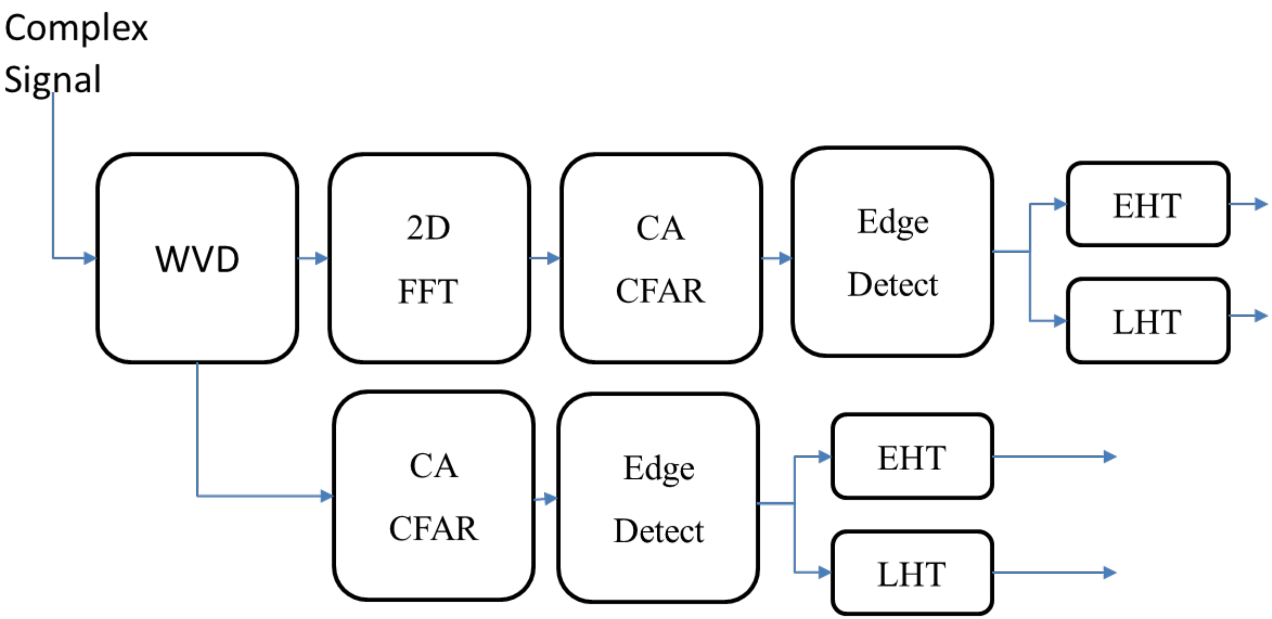
Linear HT + Non-Linear HT

- TFD analysis using the Linear Hough Transform (LHT) has already been investigated [1-2]
- But the combination of this type of Hough transform with other nonlinear Hough transforms to jointly extract TFD and AD features is not well documented.
- The Elliptical Hough Domain (EHD) is the result of producing a 5D estimate from evaluating the relative locations of a group of detections in the TFD/AD. The EHT used was based on the method described in [3].

[1] T. O. Gulum, A. Y. Erdogan, T. Yildirim and P. E. Pace, "A parameter extraction technique for FMCW radar signals using Wigner-Hough-Radon transform," 2012 IEEE Radar Conference, Atlanta, GA, pp. 0847-0852, 2012.
[2] D. L. Stevens and S. A. Schuckers, "Detection and parameter extraction of low probability of intercept radar signals using the Hough transform." *Global Journal of Research In Engineering*, 2016.
[3] H. K. Yuen, J. Illingworth, and J. Kittler. "Detecting partially occluded ellipses using the Hough transform." Image and Vision Computing 7, no. 1, 31-37,1989.

Hybrid Hough Method

- Proposing a parallel process where input data is first used to create both a AD & TFD.
- LHT: Hough accumulator of line equation
- EHT: Hough accumulator of ellipse equation
  - Xie, Yonghong, and Qiang Ji. "A new efficient ellipse detection method." Object recognition supported by user interaction for service robots. Vol. 2. IEEE, 2002.
- These have been used for classification of waveform class e.g. CW, LFM, NLFM, BSK & FC

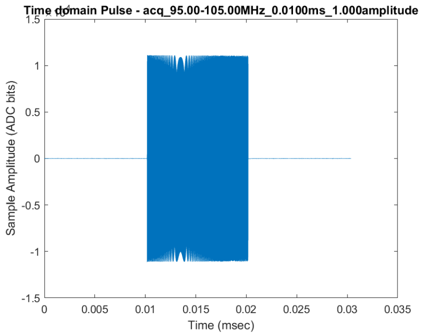


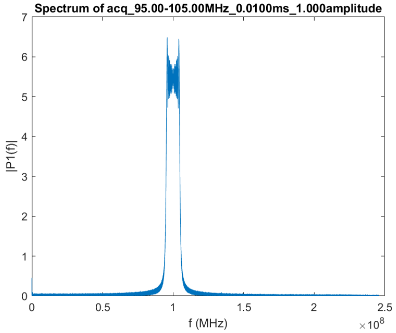
WP1.2 Outputs

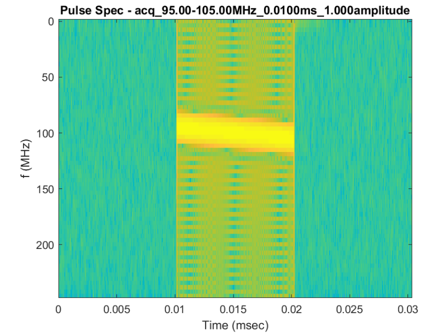
- Investigated:
  - Cross-term / Auto-term filtering
    - Understanding info content of CT / AT
  - Hybrid Hough Feature extraction
  - Sparse Shearlets Dictionaries
  - Optimal Time-Frequency Distribution Selection for LPI Radar Pulse Classification (***Radarcon 2020 paper***)
  - Inter-pulse phase analysis (***IET RSN journal paper submitted Oct 2020***)
  - Radar pulse classification using Hierarchical Time-Frequency Processing (***proposed Radarcon 2021 paper***)

Hardware Exploitation Paths

- Complimentary work on going via a DASA Theme on Invisible Battlespace (IB).
- Use of the Xilinx RFSoC (RF System on a Chip)
  - 8 x 8 Tx/Rx system with 4 GSPS / 6.5 GSPS ADC/DACs
- Can use to Tx radar waveforms and Rx waveforms
- Exploitation path for real world demonstration of novel ES concepts
- Device has the capability to be a multi-role RF sensor operating as Active Radar / Passive Radar / ES Sensor

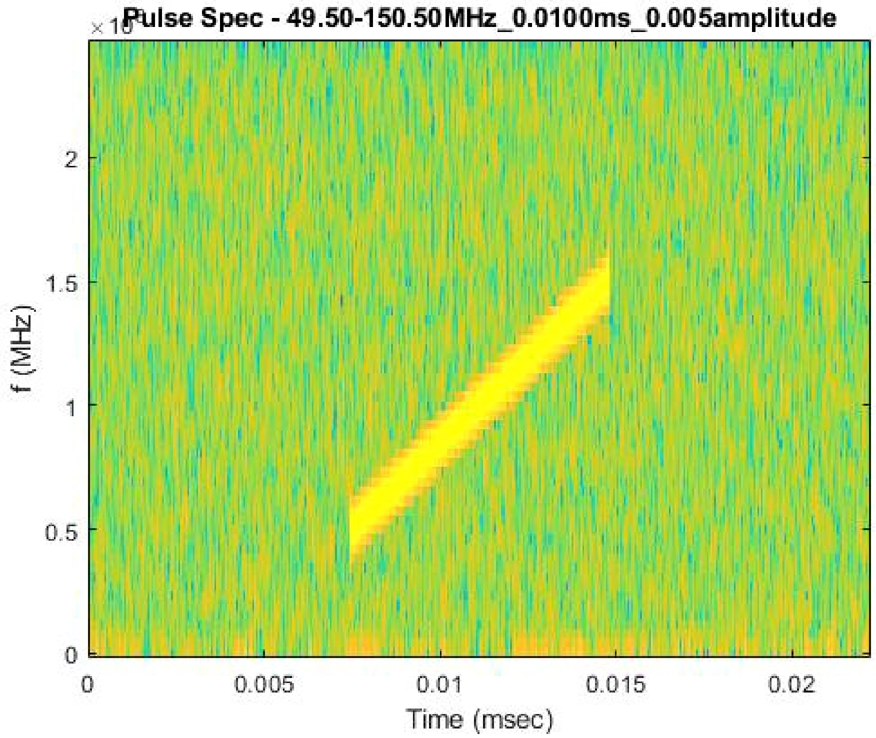






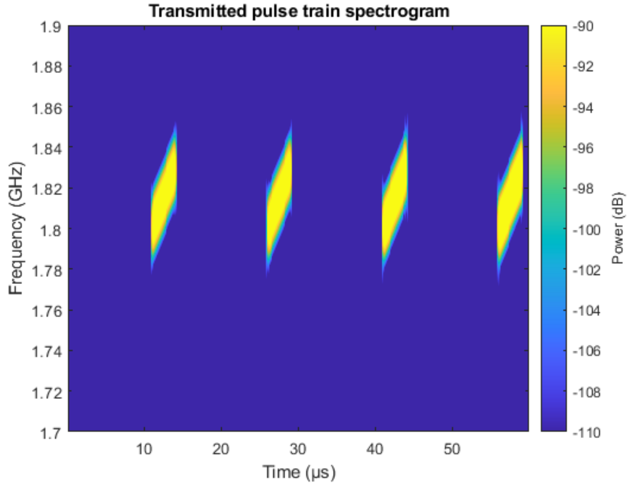
Hardware Exploitation Paths

- Example database of radar waveforms created by RFSoC



Worked Example Template 1

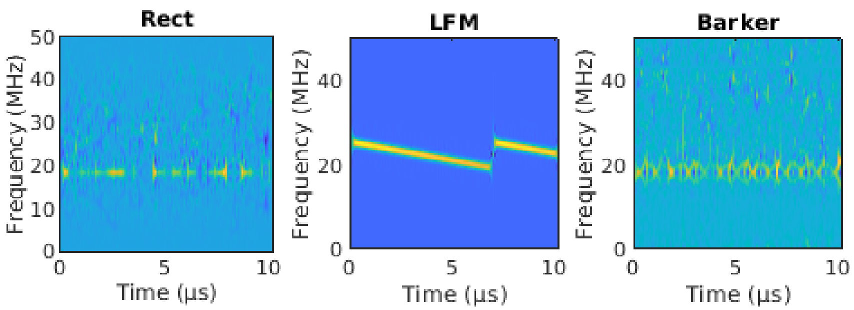
- Those new to the area should work through the Matlab example template for simulating signals for a Radar Warning Receiver (RWR)
- Defines Radar parameters
- Simulates Tx and Rx of waveform based on configured geometry
- Models RWR Rx chain / Channelizes received data
- Shows implementation of MUSIC estimator for DoA estimation
- Pseudo Wigner Ville processing applied + image processing + Hough Transform to extract PDW
- Displays estimates for PRF, Pulse length, Bandwidth, AoA and distance.



https://uk.mathworks.com/help/phased/ug/signal-parameter-estimations-in-a-radar-warning-receiver.html

Worked Example Template 2

- Focusing on classifying waveform type
- Uses waveforms
  - Radar: Rectangle / LFM / Barker Code
  - Comms: GFSK / CPFSK / B-FM / DSB-AM / SSB-AM
- Feature extract using WVD
- Save as down sampled images
- Use CNN for classification



https://uk.mathworks.com/help/phased/ug/modulation-classification-of-radar-and-communication-waveforms-using-deep-learning.html

Conclusions

- Developed a sizeable literature review of the area of 600 categorized papers from the domain representing a full survey of the state of the art
- Explained different TF and showed outputs
- Showed CNN method of classifying PDW from 4 different TFs
- Explained AT / CT of AD and how these can be leveraged
- Explained newly proposed Hybrid Hough concept
- Made good progress in leveraging both the TFD and AD to extract key features for PDW estimation
- 3 papers published/submitted
- Many more avenues to exploit.
  - Increasing EM congestion within simulation.