Reliable Discrimination of High Explosive and Chemical / Biological Artillery Using Acoustic Sensors

US Army RDECOM-ARDEC

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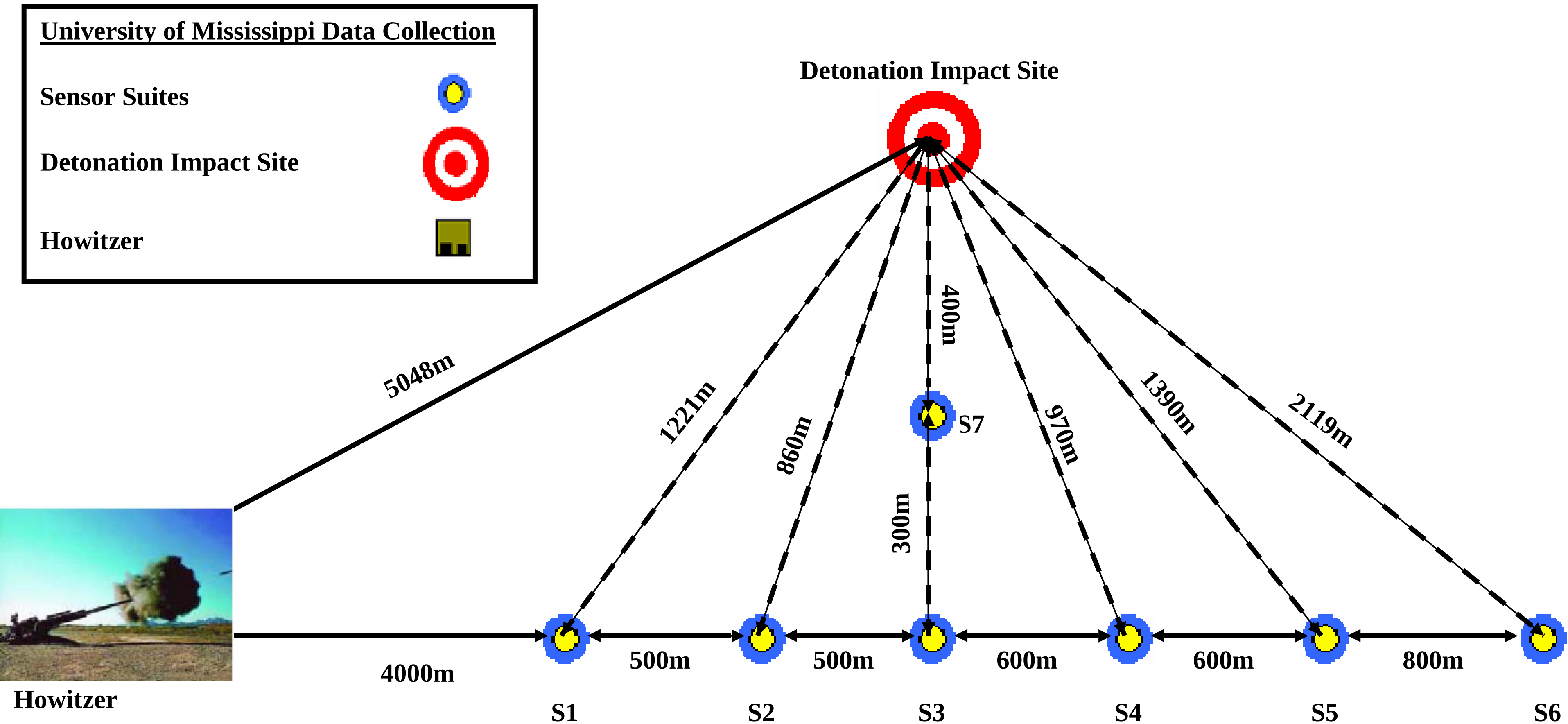
Chemical and Biological Weapon Threats and Needs

- Determining if an incoming artillery round contains High Explosive material or Chemical/Biological agent on the battlefield.
- Providing field commanders with greater response time using a stand alone acoustic sensor.
- Giving greater situational awareness to threatened soldiers.

Acoustic Signature Data Collection of Blast Events

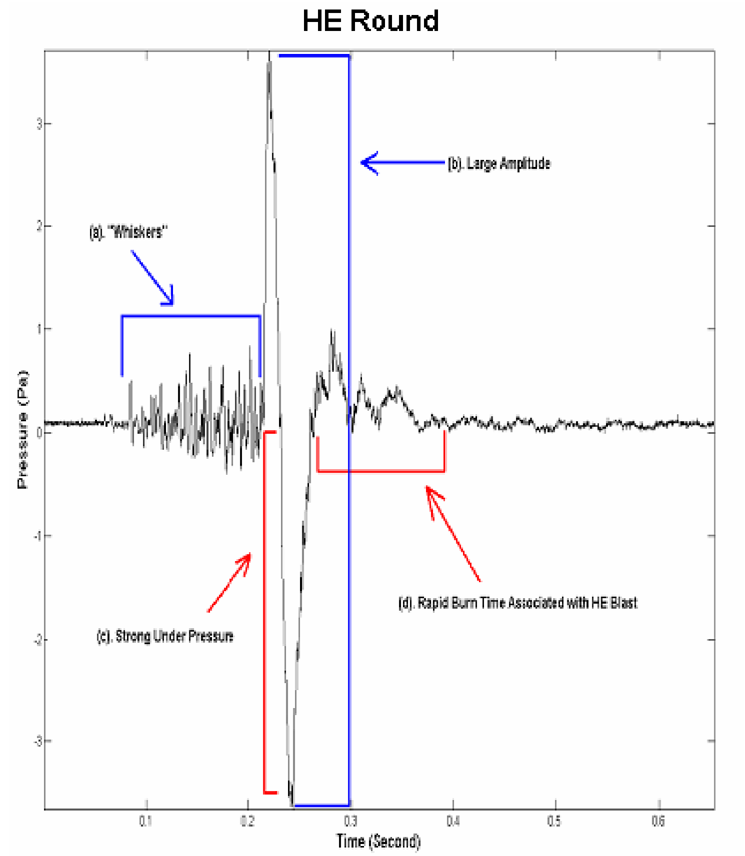
- Yuma Proving Ground Data Collection.
  - Conducted by National Center of Physical Acoustics (NCPA) in cooperation with ARDEC.
  - 39, rounds fired.
  - 3 categories of rounds were used, HE, Type A CB, and Type B.
- Dugway Proving Grounds Data Collection.
  - Conducted by DPG Team and U.S. Army Edgewood Chemical Biological Center (ECBC) .
  - 265, rounds fired.
  - 2 categories of rounds were used, HE and Type A CB.

Yuma Proving Ground (YPG) Test Layout



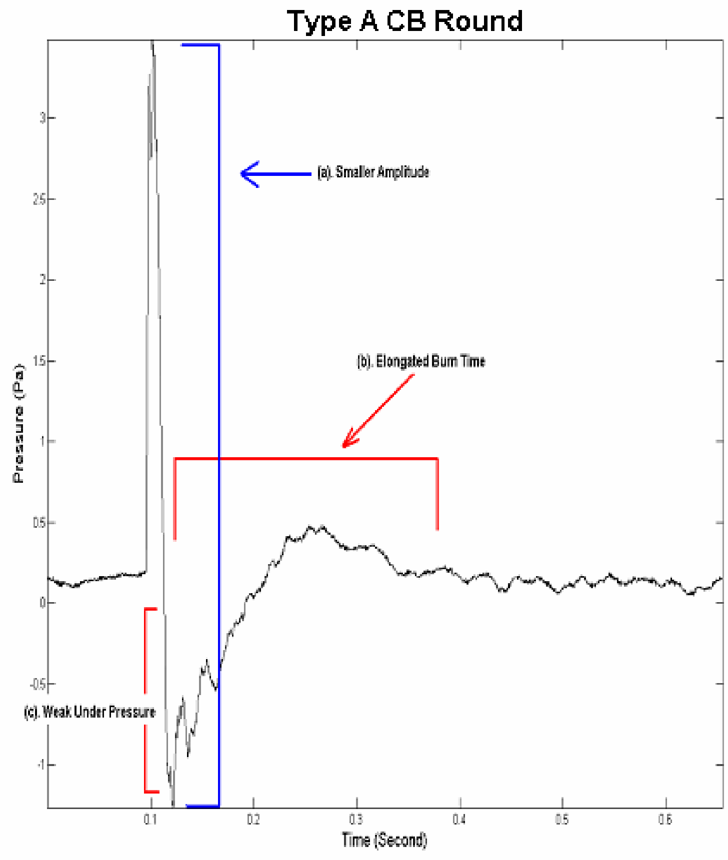
Typical Blast of HE Round

- High frequency precursors to the main blast.
  - Generated by Supersonic Shrapnel Elements.
- Large Amplitude of Main Blast.
- Large under pressure element .
  - Generated by large comparable weight of explosives rapidly burning.
- Short Duration Signatures.



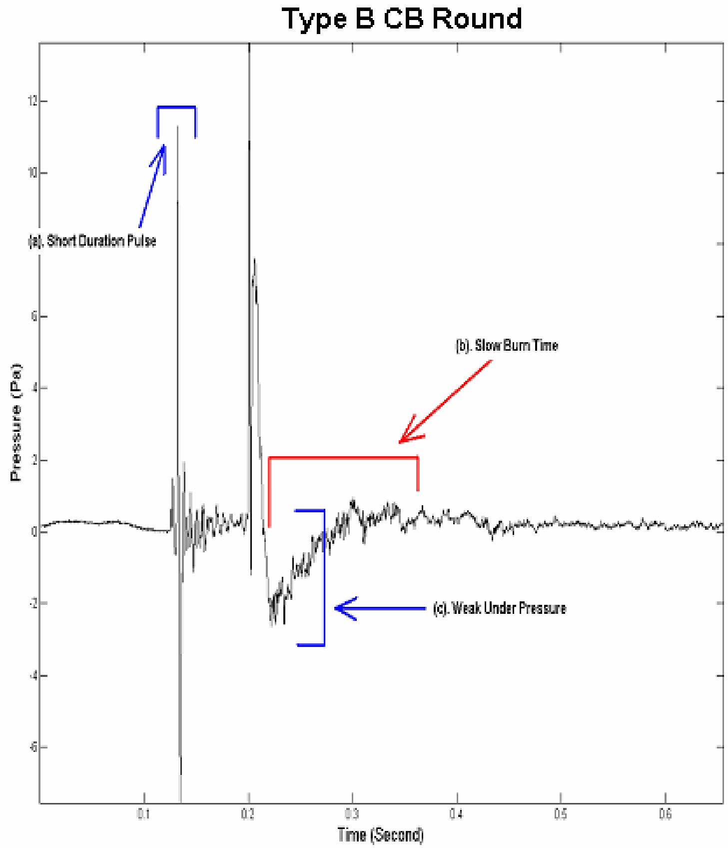
Typical Blast of Type A CB Round

- Small amplitude associated with main blast.
  - The explosive material is minimal compared to the comparable HE round type.
- Elongated burn time following main blast.
  - The deliberately slow to properly release the compounds.
- Weak under pressure.



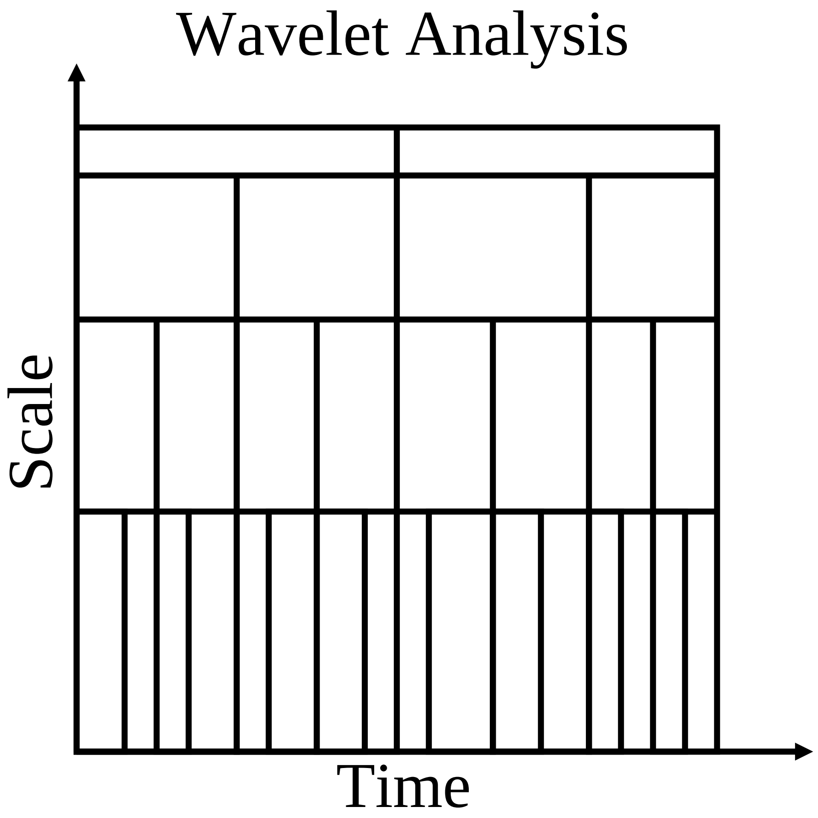
Typical Blast of Type B CB Round

- Short Duration Pulse.
  - Resulting from base ejection rounds.
- Weak Under Pressure.
  - Small amount of Explosives.
- Slow Burn Time.
  - Elongated to properly discharge contents of the round.



Wavelets

- Efficiently represent non-stationary, transient, and oscillatory signals.
- Desirable localization properties in both time and frequency that has appropriate decay in both properties.
- Provide a scalable time-frequency representation of artillery blast signature.



Discrete Wavelet Transform (DWT)

- Derived from subband filters and multiresolution decomposition.
  - Coarser Approximation.
  - Removing high frequency detail at each level of decomposition.
- Acts like a multiresolution transform.
  - Maps low frequency approximation in coarse subspace high frequency elements in a separate subspace.

Defining Parameters

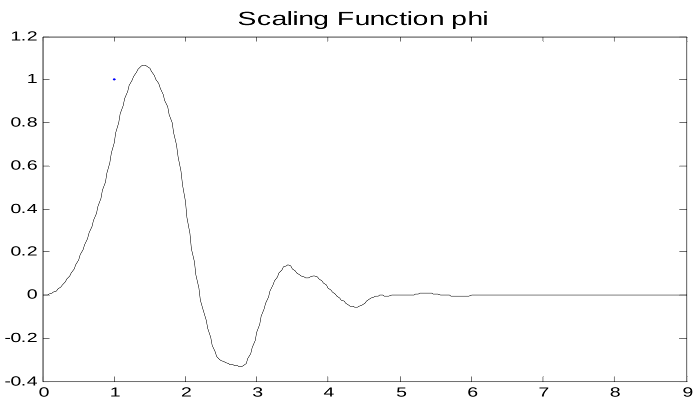
Scaling Function

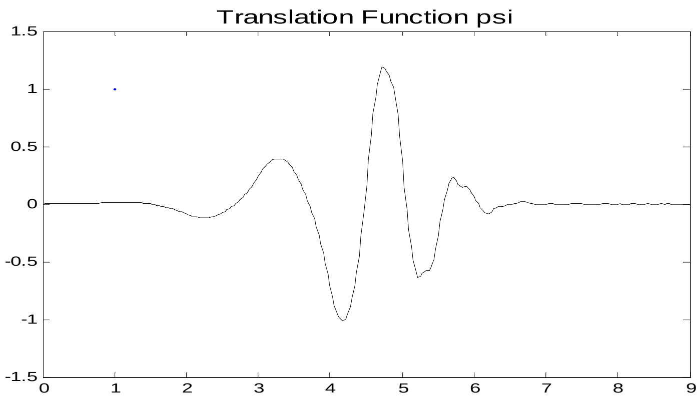
$$\phi(x) = 2^{1/2} \sum_{k=0}^{L-1} h_{k+1} \phi(2x - k)$$

Wavelet Function

$$\psi(x) = 2^{1/2} \sum_{k=0}^{L-1} g_{k+1} \phi(2x - k)$$

Daubechies Wavelet n = 5

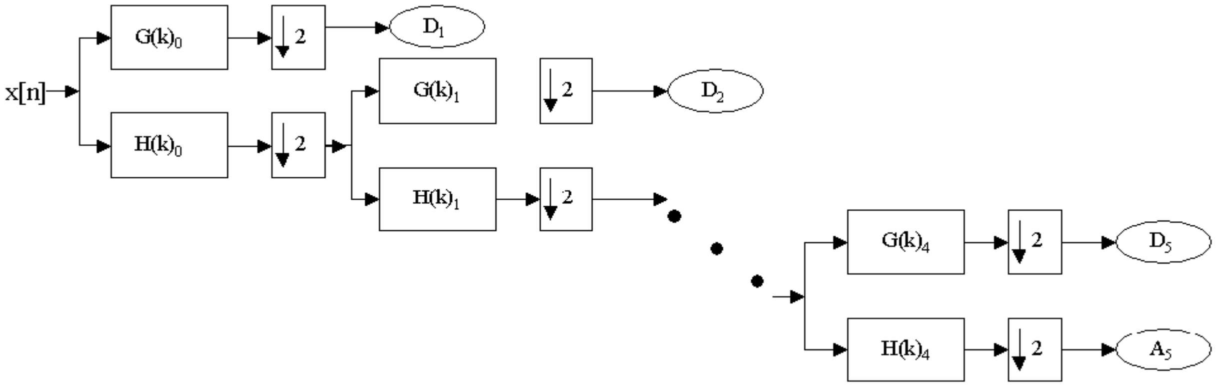




- Representation of the scaling and translation function of db5.
  - Scaling function resembles blast signature of the HE and CB rounds.
  - Provides the ability to approximate signal with the characteristic wavelet.

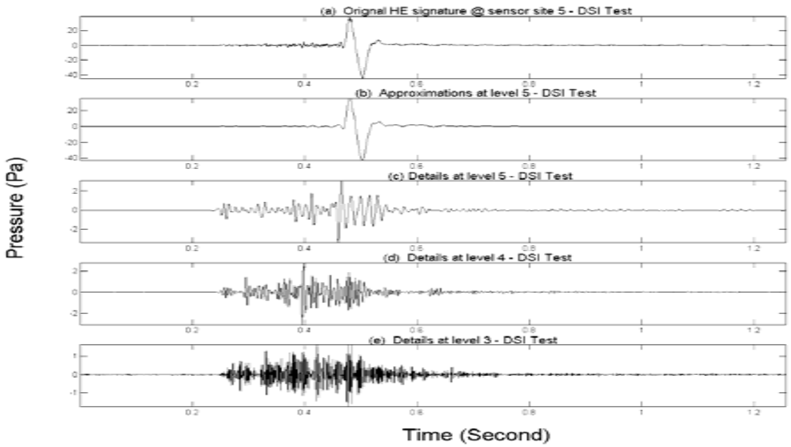
Multiresolutional Analysis

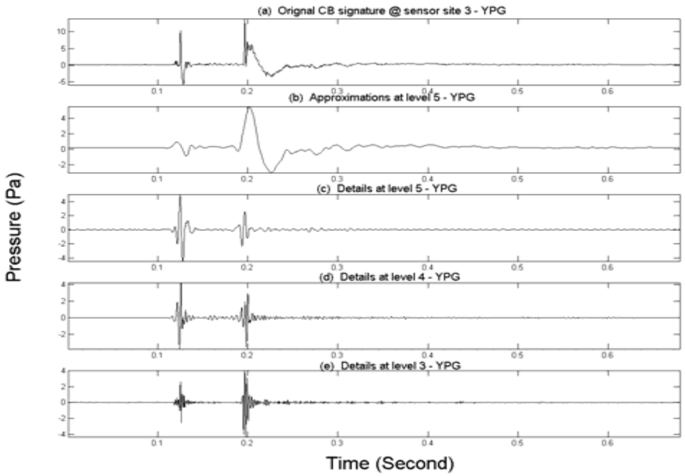
- Using a series of successive high pass and low pass filters to create a set of subspaces.
  – High pass filter obtains the details of the signatures while the low pass filter obtains a coarse approximation of the signal.
- The resulting banks of dyadic multirate filters separate the frequency components into different subbands.
  – Each pass through gives you resolution of factor 2.

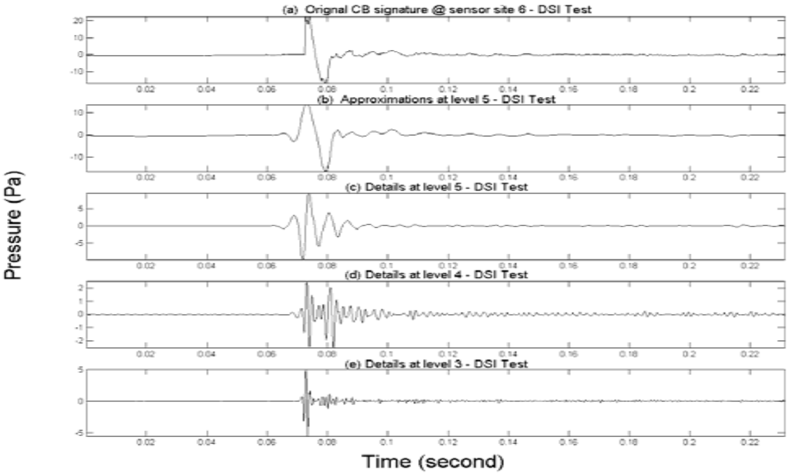


Effects of Wavelet Decomposition

- Wavelet decomposition to level 5 of three varying blast types from varying ranges.



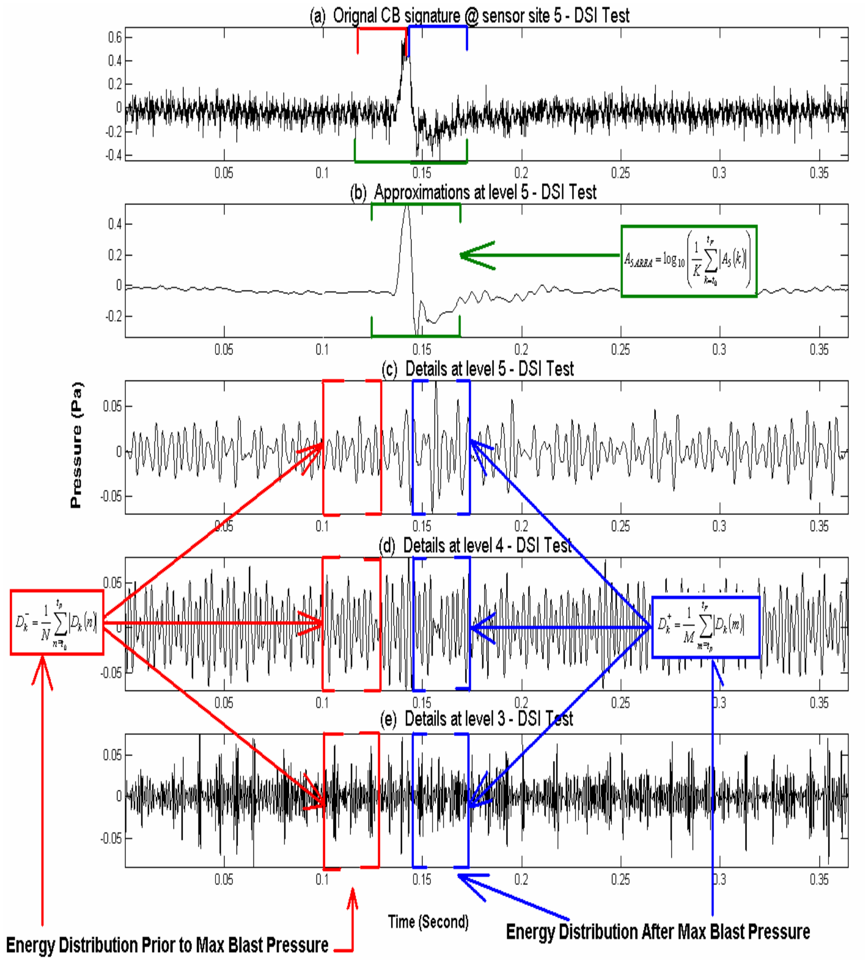


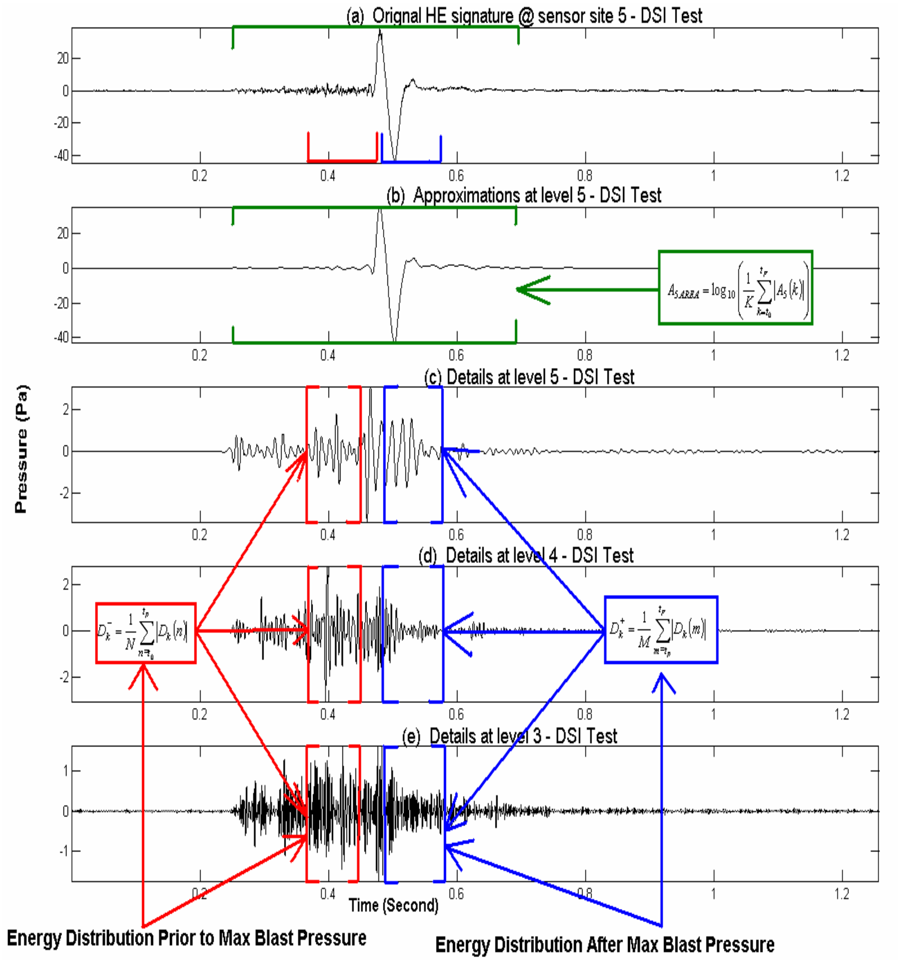


Wavelet Extracted Features

- Comprised of primitives derived from the normalized energy distributions within the details at level 5, 4, and 3 of the wavelet decomposition.
- Distribution of blast type differ greatly when taken prior to the max pressure, $D_k^- = \frac{1}{N}\sum_{n=t_0}^{t_P} |D_k(n)|$, with respect to distribution after the max blast, $D_k^+ = \frac{1}{M}\sum_{m=t_P}^{t_F} |D_k(m)|$.
- Resulting Ratio. $x_{Dk} = \log_{10}\left(\frac{D_k^-}{D_k^+}\right)$
- A5 area is a feature derived from wavelet coefficients at level 5.
- Integrating the magnitude of the area for the coefficients between the start and stop times.
- $$A_{5AREA} = \log_{10}\left(\frac{1}{K}\sum_{k=t_0}^{t_F} |A_5(k)|\right)$$

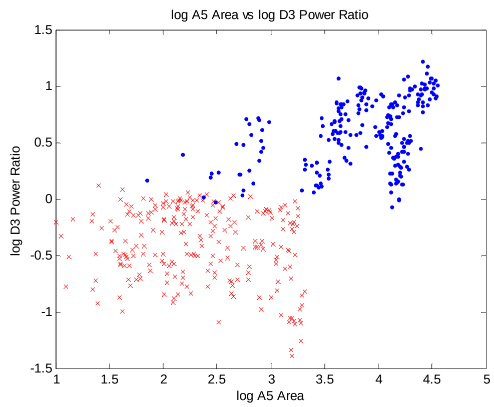
Extracted Features Using DWT

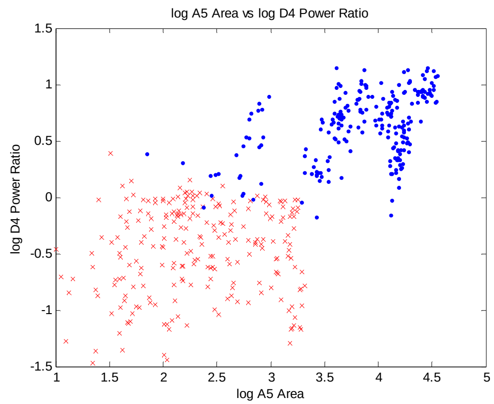




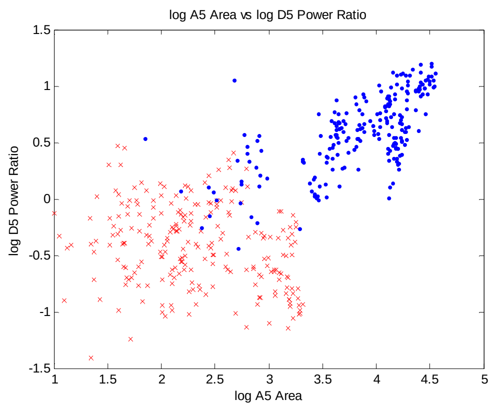
4-tuple Feature Space

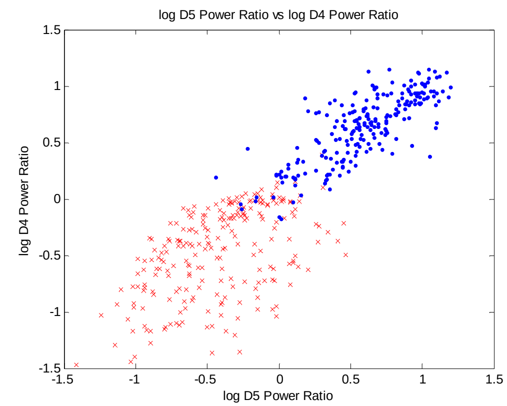
- This energy ratio leads to the discover of 4 features with A5 area that are not amplitude dependent.
- Our n-tuple feature space thus becomes a 4-tuple space, $x^p = \left[x_{D5}^P, x_{D4}^P, x_{D3}^P, A_{5AREA}^P \right]$, to be applied for classification.

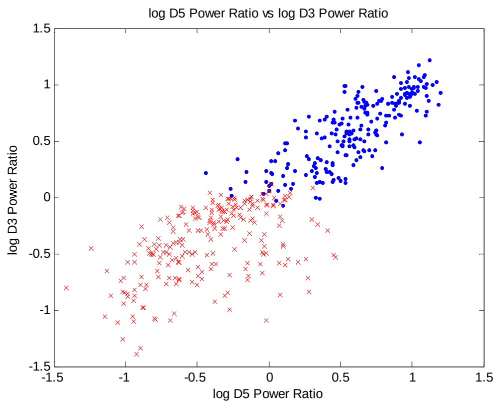


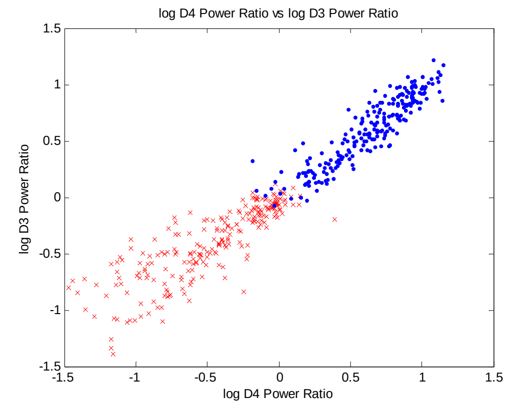


2-D Feature Space Realization



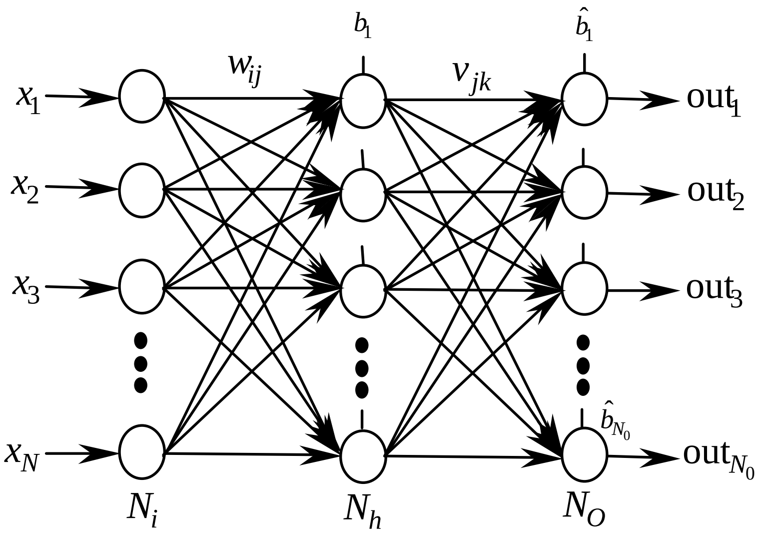






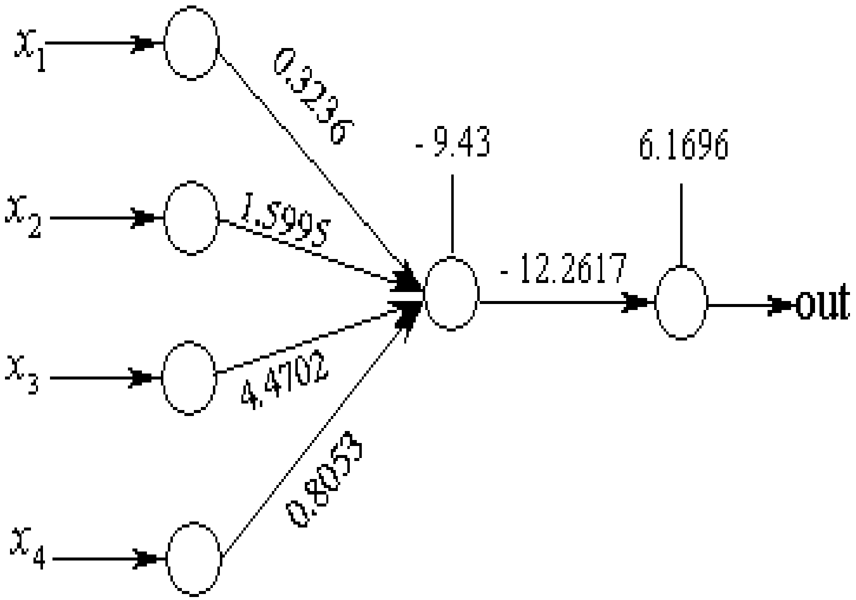
Neural Network

- Realize non-linear discriminant functions and complex decision regions to ensure separability between classes.
- Standard Multilayer Feedforward Neural Network.
- Number of hidden layer neurons depend on complexity of required mapping.



Results of Training Neural Network to DSI Data

- Feature Space created using DWT.
  - 4-tuple feature vector.
  - $x^p = \left[x_{D5}^P, x_{D4}^P, x_{D3}^P, A_{5AREA}^P\right]$
  - 22 randomly selected vectors from 461 signatures.
- Trained Neural Network to trained output data of 0.
  - Single hidden layer neuron.
  - Total error in equation after training is less then 5e-3.
  - Learning rate of 0.1.



Results of HE/CB Discrimination

- Experiment 1.
  - Applying a neural network with the weights in the table 1 to DPG data, 99.1% Correct Classification.

w_{i1}	w_{i2}	w_{i3}	w_{i4}	v_{j1}
11.6967	0.5343	-0.4958	-2.4991	-13.4966
4.6377	1.2455	3.5569	5.3068	13.3761
4.7023	0.9875	7.3951	8.902	-15.3761
-5.2246	1.481	2.6982	4.1203	-19.6513
-2.8169	1.4847	-18.9732	-23.6088	-14.286

- Experiment 2.
  - A neural network containing 4 hidden layer neurons trained using entire DPG dataset tested against NCPA dataset, 96.9% Correct Classification.

Experiment #	Training Data	Test Data	Classification	Percentage
1	11 CB (DSI)	225 CB (DSI)	225 CB / 0 HE	100%
	11 HE (DSI)	214 HE (DSI)	210 HE / 4 CB	98.10%
2	236 CB (DSI)	166 CB (YPG)	165 CB / 1 HE	99.40%
	225 HE (DSI)	57 HE (YPG)	51 HE / 6 CB	89.50%

Blind Results of HE/CB discrimination

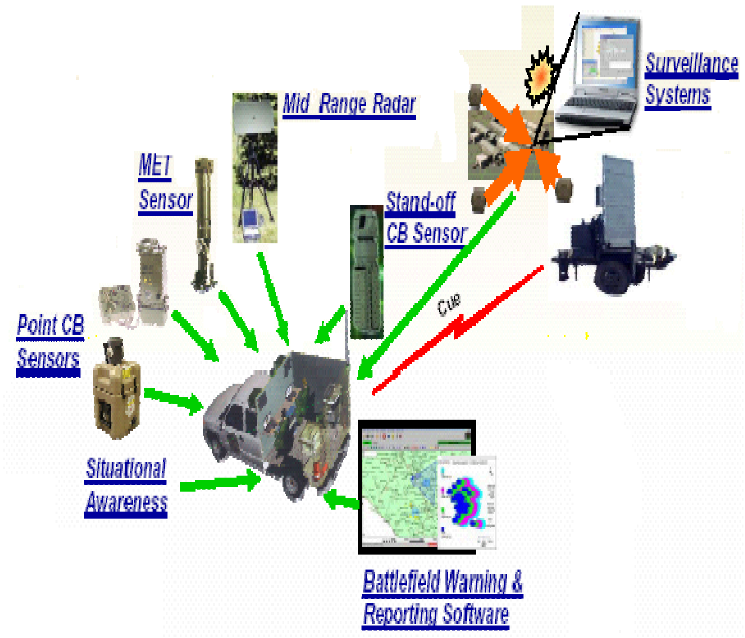
- Experiment 3.
  - Utilizing the neural network containing 4 hidden layers neurons trained against the entire "known" DPG data set was then tested against the "blind data" the results once compared with the truth resulted in 98.3% and 95.7% reliable classification.

w_{i1}	w_{i2}	w_{i3}	w_{i4}	v_{j1}
11.6967	0.5343	-0.4958	-2.4991	-13.4966
4.6377	1.2455	3.5569	5.3068	13.3761
4.7023	0.9875	7.3951	8.902	-15.3761
-5.2246	1.481	2.6982	4.1203	-19.6513
-2.8169	1.4847	-18.9732	-23.6088	-14.286

Experiment #	Training Data	Test Data	Classification	Percentage
3	236 CB (Blind)	230 CB (Blind)	226 CB / 4 HE	98.3 %
	225 HE (Blind)	184 HE (Blind)	176 HE / 8 CB	95.7 %

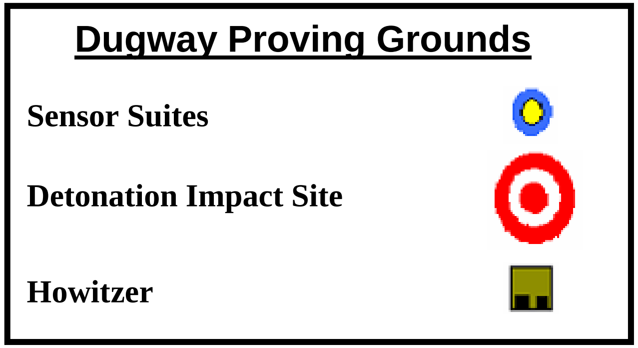
Experiment 4 Real Time Implementation

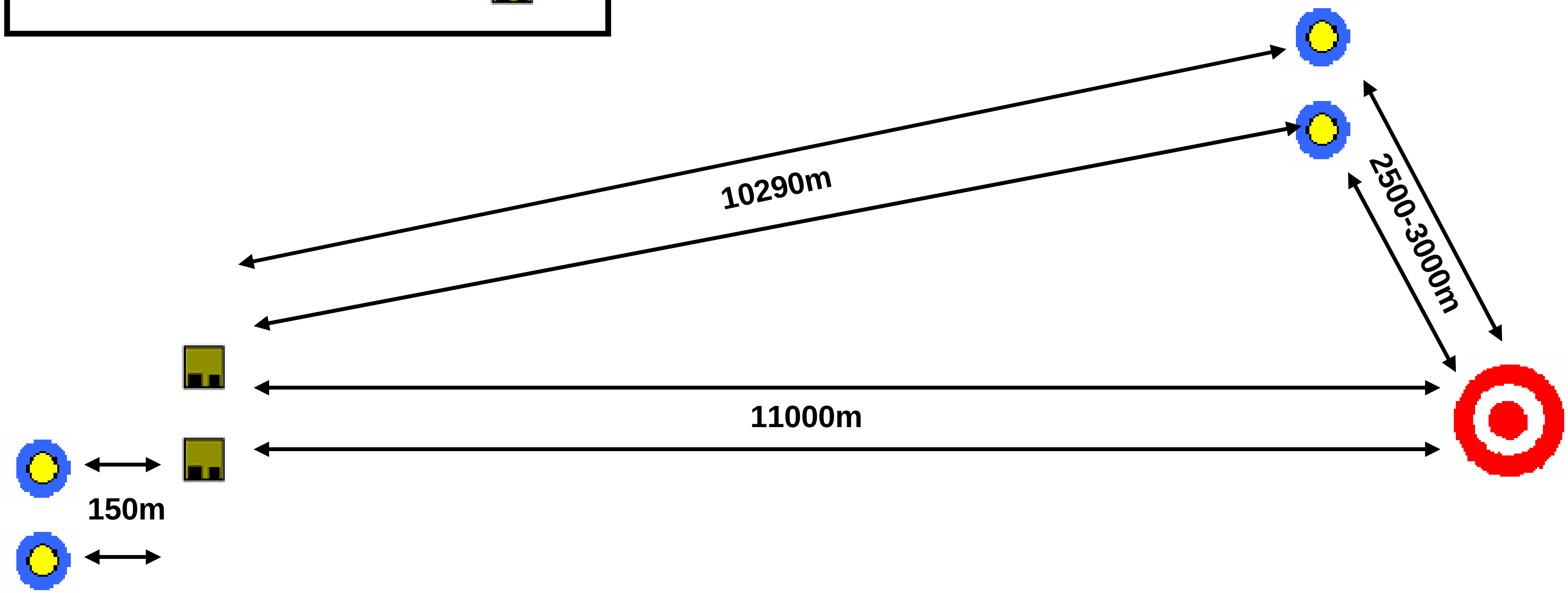
- Portable Area Warning Surveillance System (PAWSS).
  - 1yr Limited Objective Experiment (LOE).
  - Focused on the utility of cascading detection methodologies.
  - Combines Stand-off CBRN systems to address both force/installation protection.
- LOE Outcomes.
  - Operable Products leading to fully designed products that are sustainable.
  - Demonstration of capabilities within simulated battlefield environments of layered wide area cascading detection.



PAWSS LOE Test Layout

Artillery Variant	# of Rounds
HE	24
CB	48





PAWSS LOE Results

- June 19th-28th Portable Area Warning Surveillance System (PAWSS) Limited Objective Experiment (LOE).
- Implemented real time version of CBRN Discrimination at PAWSS LOE conducted by ECBC.
- 100% single volley discrimination, never tested against dual volley, still 83%, also all event starts were detected for 100%.
- Assist in transition and support of acoustic element CBRNEWS ATD extending LOE efforts.

Event Type	# of Events	Discriminated Correctly
Single Round	38	38/38; 100%
Dual Round	34	28/34; 83%

Real Time Performance

- During June 21st and June 22nd, 2005 a proof of concept test was conducted for the acoustic CBRN discrimination algorithm.
  - PAWSS Test Site, DPG.
    - Acoustic System 2.5km-3km from Impact Zone.
  - A C++, real time algorithm was tested at DPG as part of the acoustic portion of PAWSS LOE conducted by JPM for NBC Contamination Avoidance at ECBC.
  - A total of 72 HE/CB rounds were detonated.
    - A howitzer fired 24 HE, and 48 CB rounds.
- Single Round Volley Results.
  - 38 Airburst Detonation (14 HE, 24 CB), 100% Correct Classification.
- Multiple Round Volley.
  - CBRN Algorithm Never Benchmarked in Lab vs. Multiple Rounds.
    - 2 Rounds simultaneously fired followed by a 3rd round fired soon as possible.
  - 34 Airburst Detonation (10 HE, 24 CB).
    - 17 events, each event consisted of 2 detonations.
  - 83% Overall Correct Discrimination of HE/CB.
    - 100% discrimination on all HE rounds.
    - 100% acoustic detection of all events.
    - 28 correctly discriminated from 34 detonations.
    - Shortcomings occur within the data acquisition process, limited by processing window size.

Conclusion

- Features extracted facilitate robust classification.
  - Reliable discrimination of CB rounds, 98.3% or greater of single volley events.
- The features this algorithm is based on go beyond previous amplitude dependent features.
  - Degradation due to signal attenuation and distortion is nullified and exceeds 3km in range propagation.
- Scalable time frequency representation uncovered non-readily detectable features.
  - Subband components remove higher frequency noise features.
  - Isolating the details of higher oscillatory components.
- Real time verification at PAWSS LOE of CBRN Discrimination Program Implemented in C++.
  - Single volley round discrimination in real time for all variants was 100%.
  - Dual volley round discrimination in real time for all variants was 83%, and detected an event 100% of the time.
- Wavelets can be possibly used to discriminate varying types of artillery projectile launches from impacts independent of range.
  - Utilizing wavelets and other signal processing techniques to perform a similar task as described within with refinement for the problem.
- Future Considerations.
  - Networking of sensors can provide TDOA abilities to further localize a threat.

Acknowledgements

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- David Sickenberger and Amnon Birenzvige at Edgewood Chemical and Biological Center (ECBC) providing detailed documentation about the test at DSI.
- Edward Conley at ECBC allowing us to participate in the PAWSS LOE.