Reliable Discrimination of High Explosive and Chem/Bio Artillery Using Acoustic Sensors

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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.

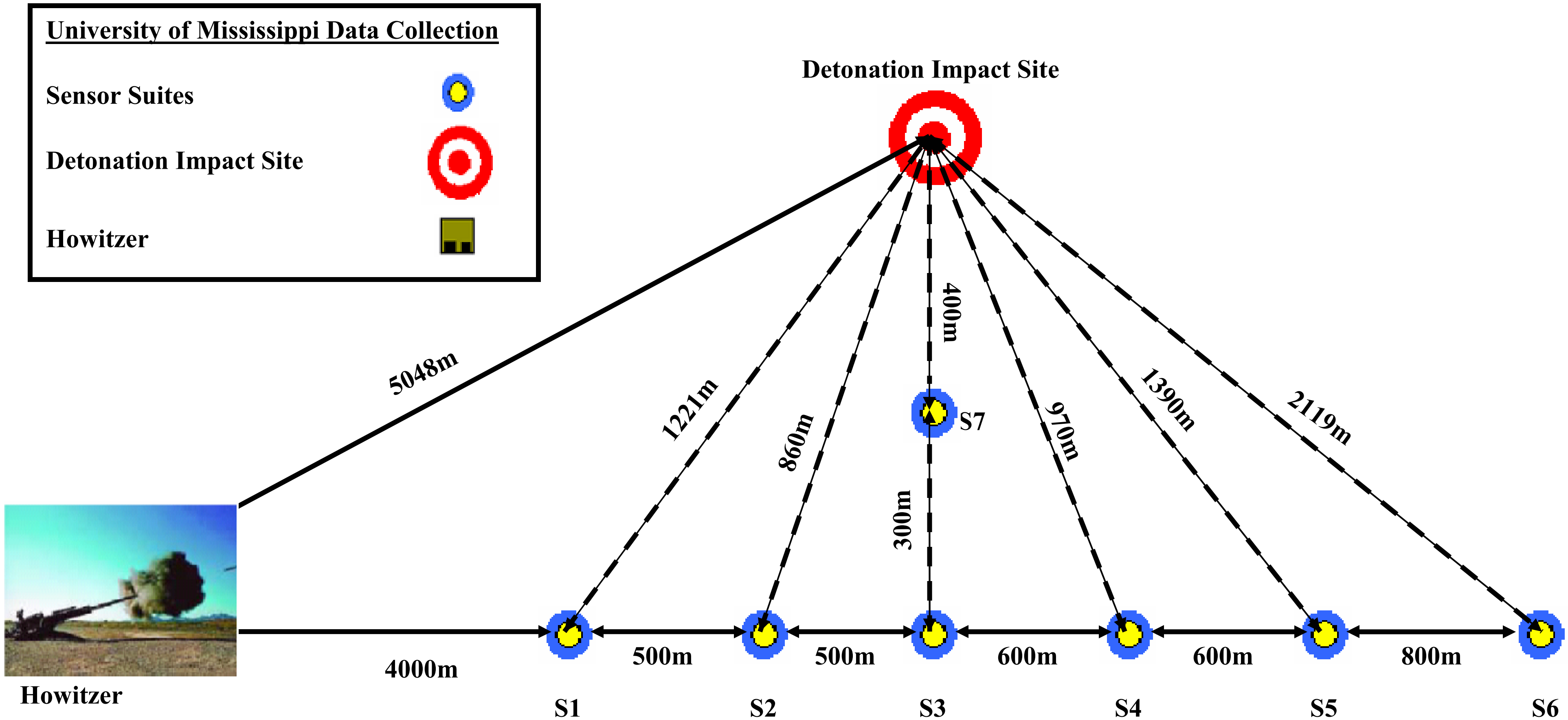
Motivation and Purpose

- ARMY is currently developing Acoustic Sensor Systems for battlefield surveillance.
- The **long range propagation** of acoustic blast waves from heavy artillery blasts introduces a feature for using acoustics and other disparate sensor technologies for the early detection, localization, and identification of CB threats.
- This added information integrated into the COP will.
  - Allow a field commander to make **rapid and accurate judgments** that insure greater safety and lessen exposure for the soldiers.
  - Could help **reduce the time-consuming, manpower** intensive and dangerous tasks associated with identifying the airburst.
- Our work is intended to promote the reliability associated with using acoustic sensor technologies to discriminate between conventional, i.e. high explosive (HE), and CB artillery blasts using features that remain robust with long range wave propagation and degradation, firing time and detonation point (air/ground).

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

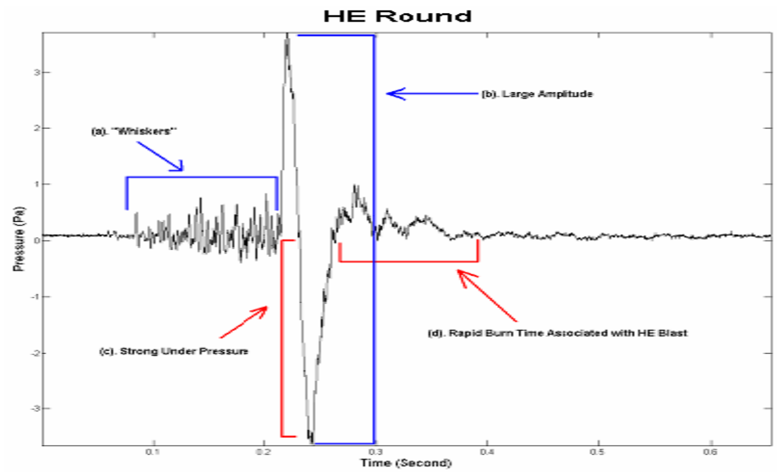


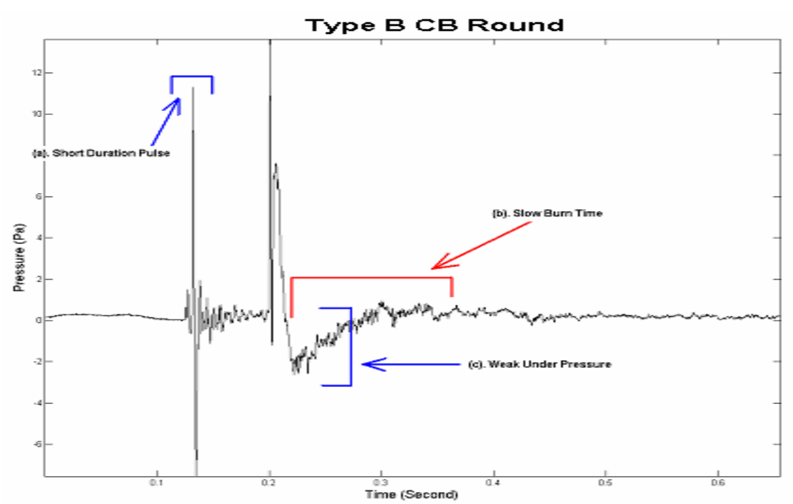
Typical Round Variants

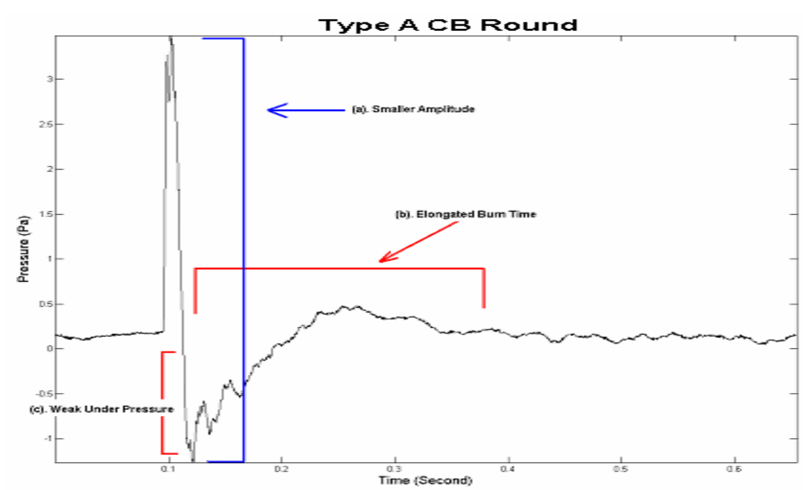
HE rounds display precursors to the main blast generated by Supersonic Shrapnel Elements.

CB Type A rounds display an elongated burn time and a weak underpressure.

CB Type B rounds display a short pulse prior to the main blast. The main blast displays an elongated burn time followed by a weak underpressure.

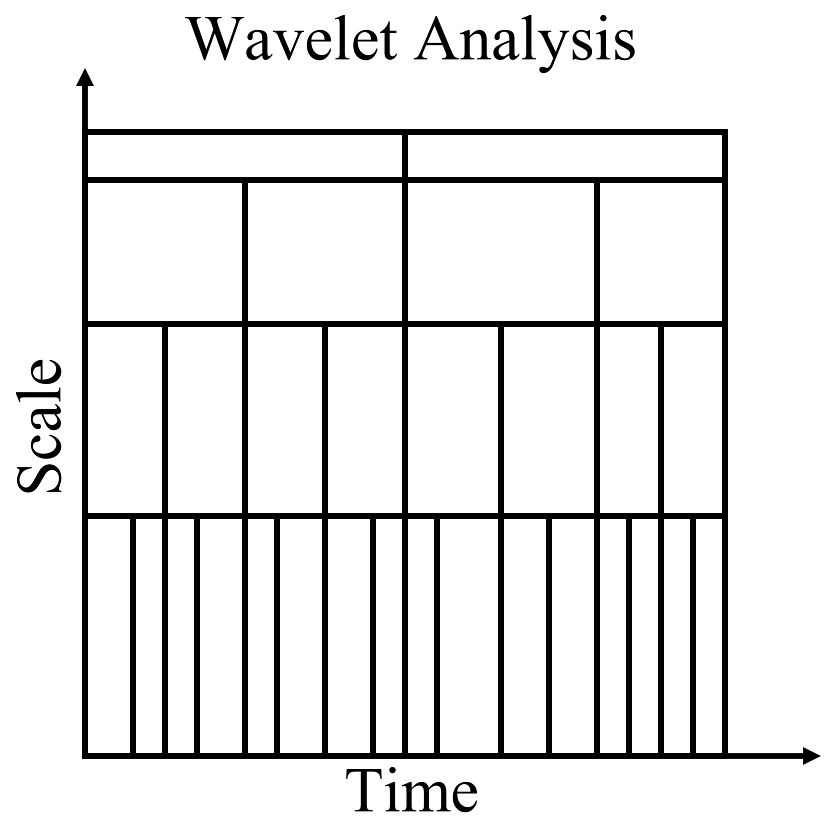






Wavelets

- 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

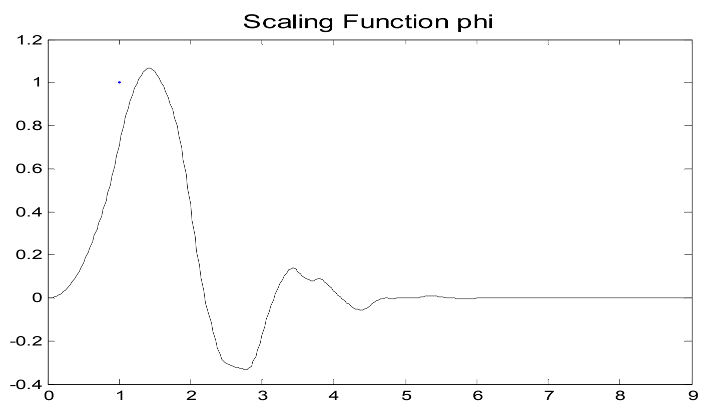
Scaling Function

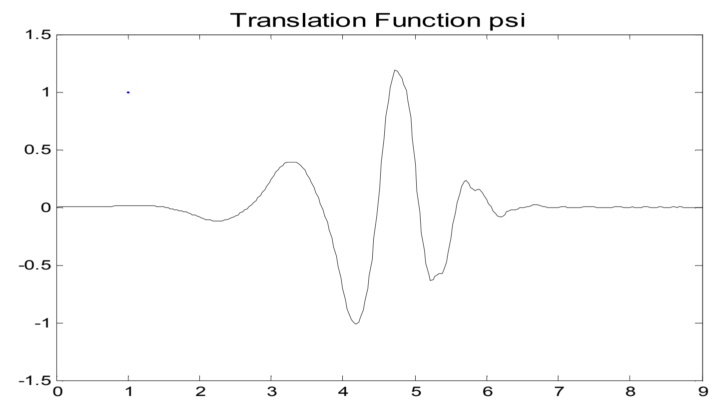
$$\phi(x) = 2^{1/2} \sum_{k=0}^{L-1} h_{k+1} \phi(2x - k)$$

Wavelet Function

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

Daubechies Wavelet, n = 5

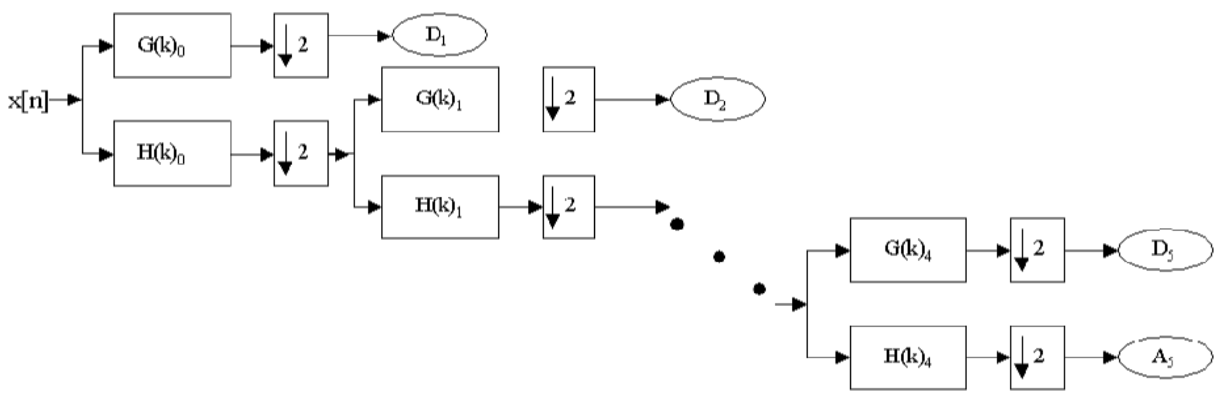




- Representation of the scaling and translation function of db5.
  - Scaling function resembles blast signature of the HE and CB rounds.
  - Provides the ability to approximate signal with the characteristic wavelet.

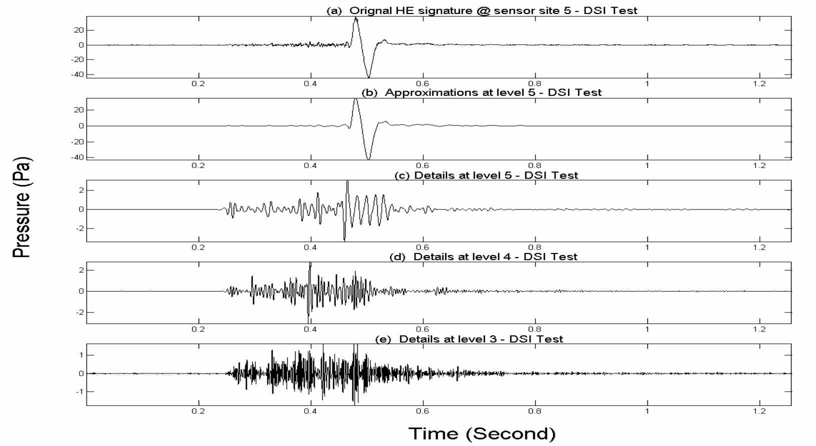
Multiresolutional Analysis

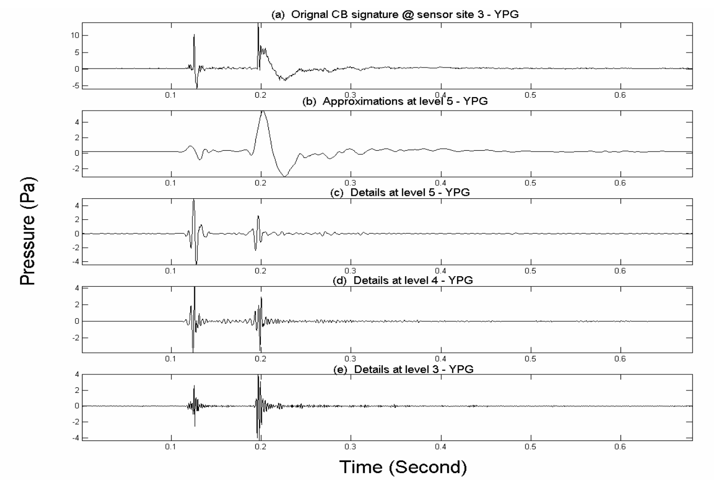
- Using a series of successive high pass and low pass filters to create a set of subspaces.
  - High pass filter obtains the details of the signatures while the low pass filter obtains a coarse approximation of the signal.
- The resulting banks of dyadic multirate filters separate the frequency components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

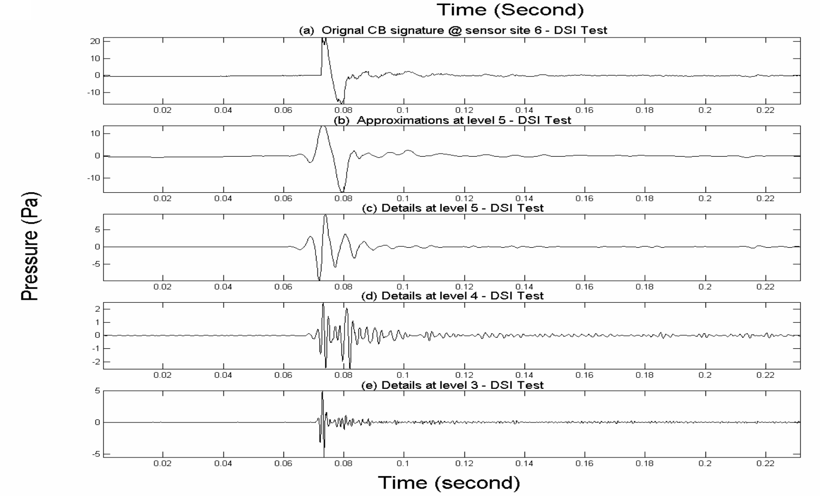


Effects of Wavelet Decomposition

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



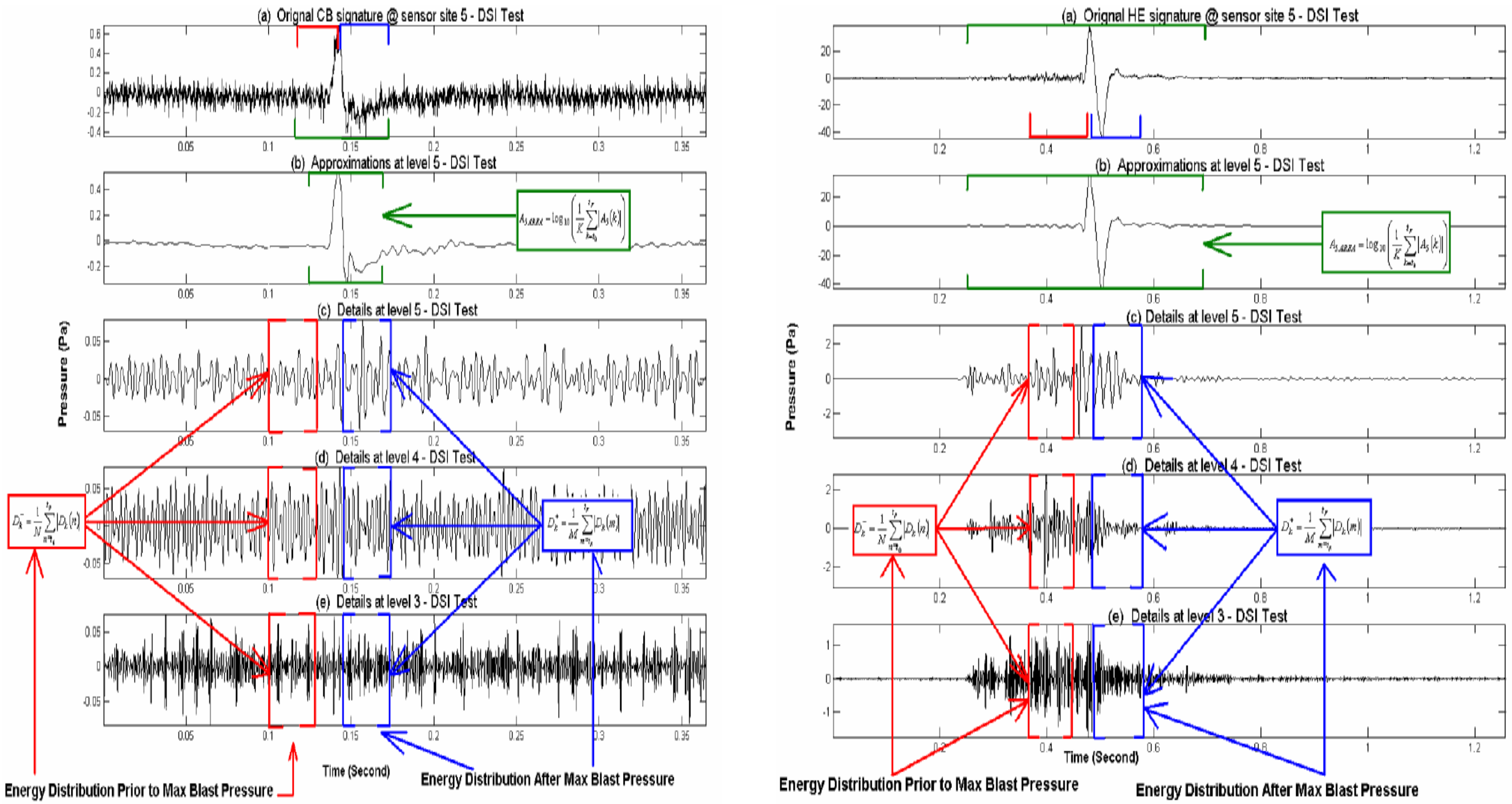




Wavelet Extracted Features

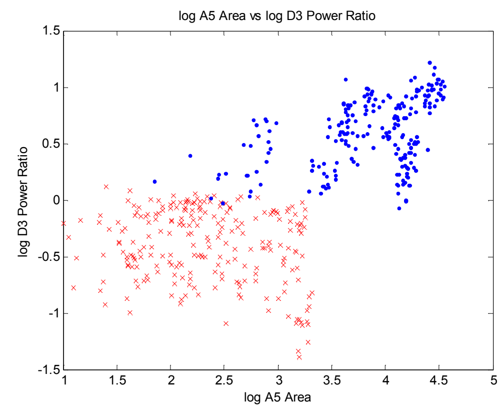
- Comprised of primitives derived from the normalized energy distributions within the details at level 5, 4, and 3 of the wavelet decomposition.
- Distribution of blast type differ greatly when taken prior to the max pressure, $D_k^- = \frac{1}{N}\sum_{n=t_0}^{t_P} |D_k(n)|$, with respect to distribution 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.
- $$A_{5\,AREA} = \log_{10}\left(\frac{1}{K}\sum_{k=t_0}^{t_F} |A_5(k)|\right)$$

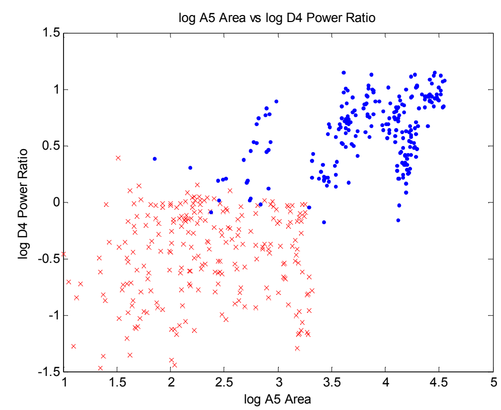
Extracted Features Using DWT



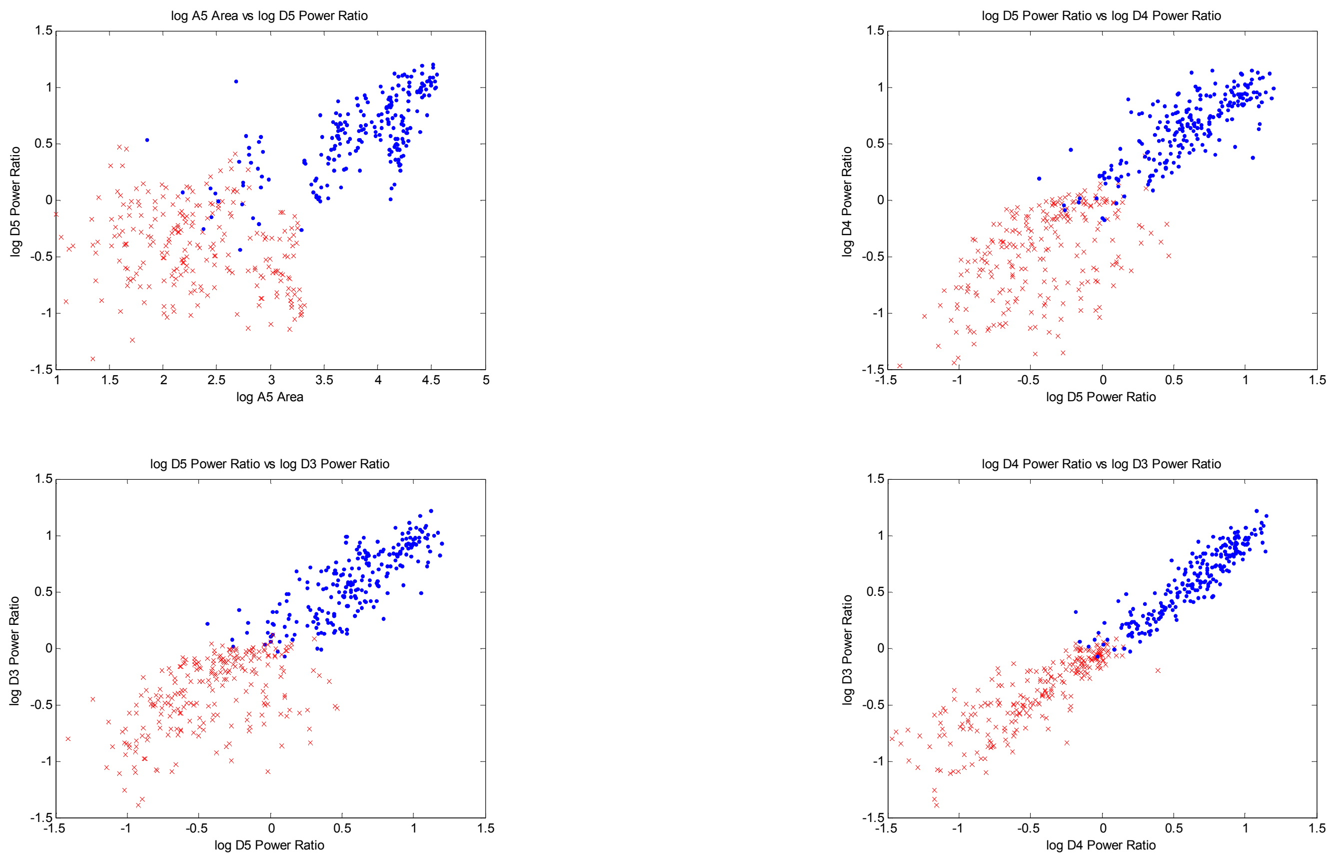
4-tuple Feature Space

- 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.



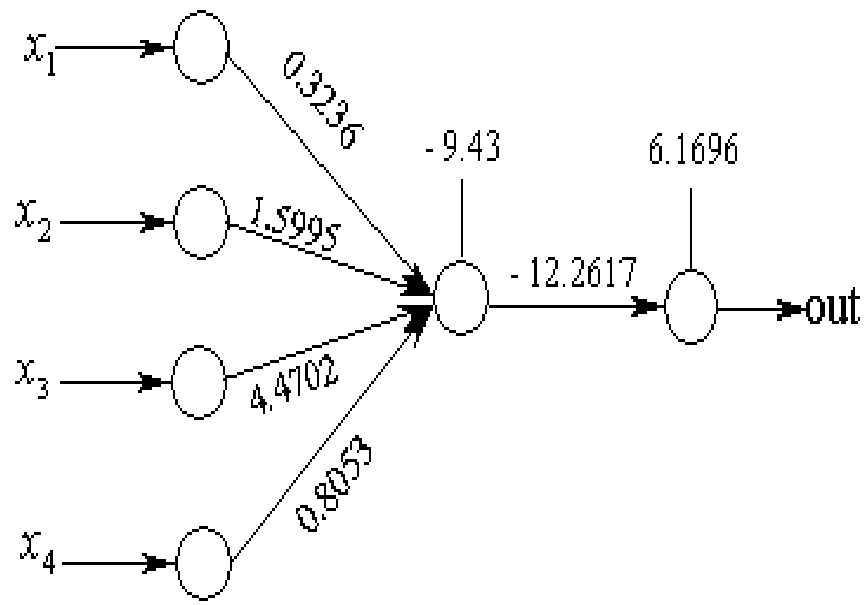


2-D Feature Space Realization



Results of Training Neural Network From Dugway Data

- Feature Space created using DWT.
  - 4-tuple feature vector.
  - $x^p = \left[x^P_{D5}, x^P_{D4}, x^P_{D3}, A^P_{5AREA}\right]$
  - 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.
- Experiment 2.
  - A neural network containing 4 hidden layer neurons trained using entire DPG dataset tested against NCPA dataset, 96.9% 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 #	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

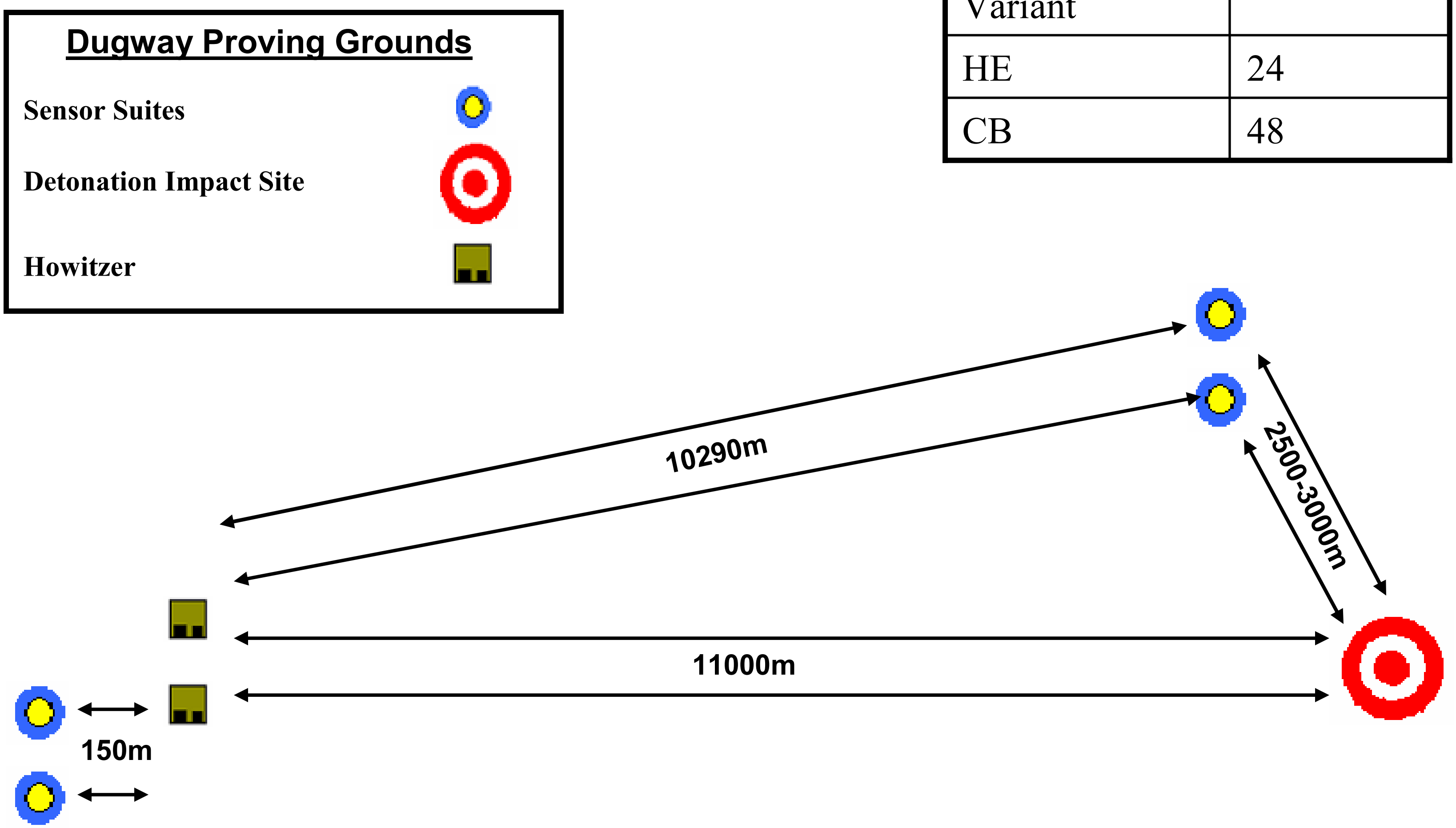
Experiment #	Training Data	Test Data	Classification	Percentage
3	236 CB (Blind)	230 CB (Blind)	226 CB / 4 HE	98.3 %
	225 HE (Blind)	184 HE (Blind)	176 HE / 8 CB	95.7 %

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



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 at elevations of 400m-1000m.
  - 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.

PAWSS LOE Summary

- PAWSS LOE was conducted June 19th-28th.
- 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%

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.

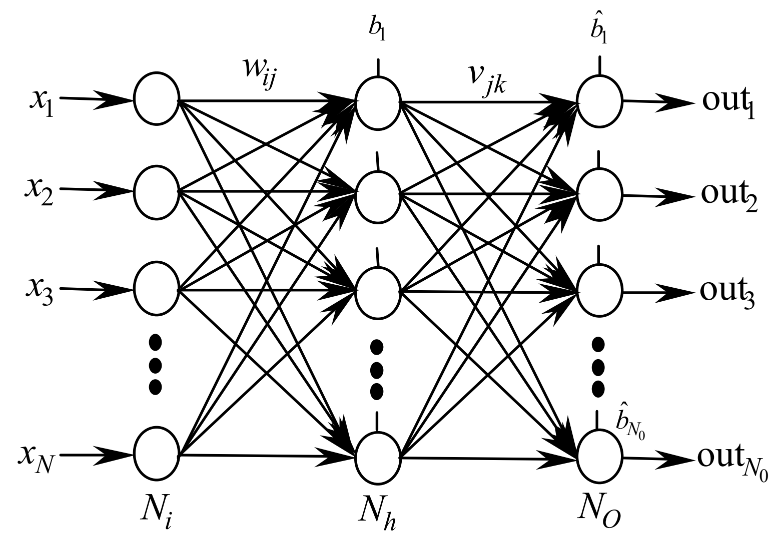
Acknowledgements

- Chris Reiff from Army Research Lab for his assistance in providing data sets from the DSI test.
- David Sickenberger and Amnon Birenzvige at Edgewood Chemical and Biological Center (ECBC) providing detailed documentation about the test at DSI.
- Edward Conley from JPM NBC Contamination Avoidance Office allowing us to participate in the PAWSS LOE.

Backup

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.



Typical Met. Condition at PAWSS Test