

# Detection, Classification and Tracking

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# Detection, Classification and Tracking of Targets in Distributed Sensor Networks

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# Overview

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- ❑ Detection: Is there a target?
  - ❑ Localization: If so, where is it?
  - ❑ Tracking: Which way is it going?
  - ❑ Classification: What kind of target is it?
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# Collaborative Signal Processing

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- Distributed processing
    - Raw signal is processed locally. Summary statistics are stored locally and transferred between nodes on-demand.
  - On-demand processing
    - No automatic publish-subscribe. Nodes are on standby unless requested by query.
  - Information fusion
    - Hierarchical information fusion. Progressively lower bandwidth information over progressively larger regions.
  - Multi-Resolution Processing
    - Depending on query, some tasks may require a finer spatial/temporal resolution and others lower.
    - Example: Reliable target detection might be performed with coarse space-time resolution, but classification might require finer space-time processing.
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# Space-time sampling

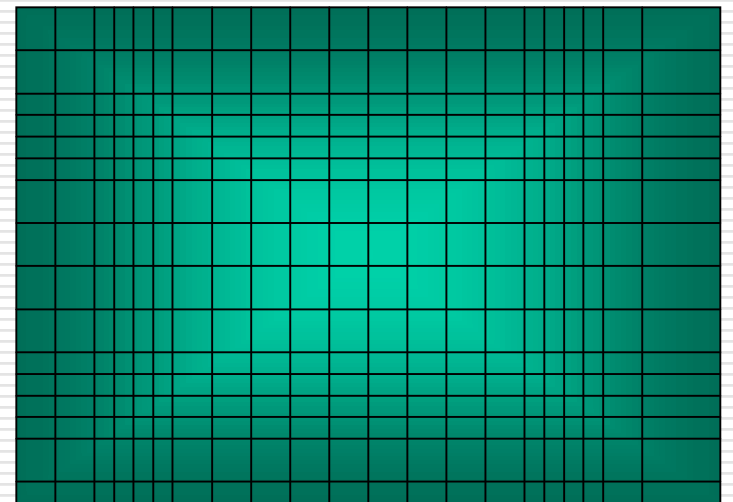
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- Each object generates a time-varying, space-time signature field that can be sensed by different modalities: acoustic, seismic, thermal
  - Density of nodes should be commensurate with rate of spatial variation of phenomenon
  - Temporal sampling should be commensurate with required bandwidth
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# Space-Time Cells

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- Cell is unit of processing
- How to select the size of the cells?
  - Velocity of target
  - Rate of variation of field (decay exponent)
- Ideally: dynamically adjust size depending on predictions of above.



# Detection and Tracking Framework

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- ❑ Nodes in boundary cells are kept in the active mode in-order to detect target.
  - ❑ Manager node for cell determines location of target from energy detector output of nodes.
  - ❑ Manager predicts location of target from last  $M$  locations
  - ❑ Predicted positions are activated in advance of the target arrival.
  - ❑ Once target is detected in the new cell, nodes in previous cell is switched to standby.
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# Detection Techniques

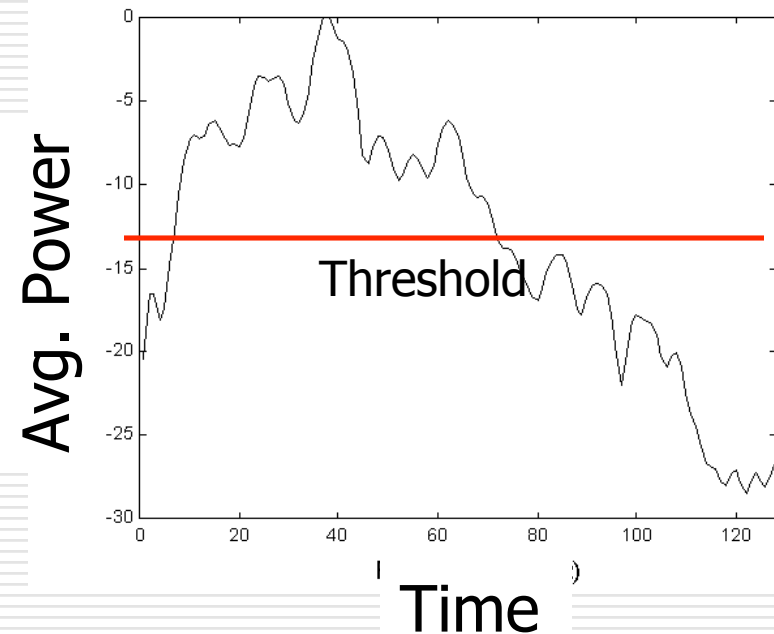
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- Goal: Find a distinct feature that can be used to cheaply (energy-wise) and reliably detect target.
  
  - Amplitude-based
    - Detect if signal energy crosses threshold
  
  - Frequency-based
    - Detect if a particular frequency component is dominant in the signal.
    - Detect if the signal has a high degree of periodicity.
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# Energy-based Detection

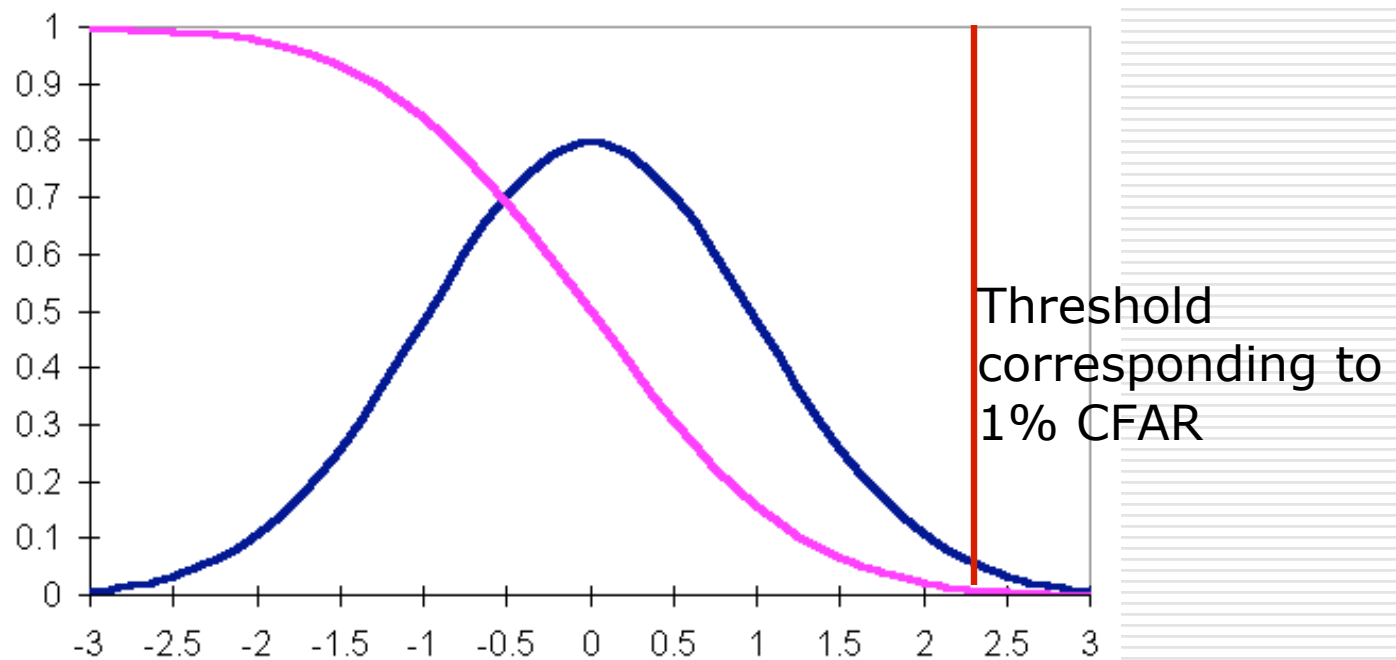
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- ❑ Each node computes running average of signal power over a window of time.
- ❑ Sampling rate determined by target signature bandwidth
- ❑ Window size determined by expected signature duration.
- ❑ Event detected when energy exceeds threshold



# Energy-based Detection (2)

- How to choose threshold?
  - Model noise floor as a Gaussian RV and find its mean and variance from the statistics of background noise.
  - Adjust threshold dynamically so that detector maintains constant false alarm rate



# Energy-based Detection (3)

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- Final output of detector
    - Onset time when detector output exceeded threshold
    - Time of maximum signal energy (closest point of approach - CPA)
    - Detector output at time of CPA.
    - Offset time when detector output falls below threshold.
  - Communicate Detections to Manager for cell.
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# ASIC implementations of Detector

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- Periodicity estimation in hardware
  - “What is the degree of periodicity in the signal?”
  - Vehicles have high degree of periodicity
- Detection scheme
  - 1-bit per sample (0 or 1)
  - Auto-correlation-based detector (not explained here)
- Power considerations
  - $<1\mu\text{W}$  power consumption
  - 20,000 times less than power consumption of zigbee radio ( $\sim 20\text{mW}$ )

A wakeup detector for an acoustic surveillance network: Algorithms and VLSI Implementation: Goldberg, Andreaou et al, Johns Hopkins

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# Distributed Detection

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- Relatively mature research topic
    - Lots of work in early 90s
    - Distributed Detection and Data Fusion - P. Varshney (Springer-Verlag)
  - How can a cluster of  $n$  nodes reliably combine their detections?
    - Make local decision and aggregate decision
    - Local decision rule being a likelihood ratio test leads to global optimal solution.
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# Localization

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- Manager of cell combines detections to localize target
  - Available: signal power detected at different node locations
- Assuming isotropic propagation and exponential attenuation for the target energy source,

$$y_i(t) = \frac{s(t)}{\|\mathbf{r}(t) - \mathbf{r}_i\|^\alpha}$$

- Compute ratios  $y_i(t)/y_j(t)$  to eliminate the unknown  $s(t)$ .
    - $n-1$  independent equations
    - Solve for unknown target location using non-linear Least Squares
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# Tracking

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- Given target locations at past instants, fit data samples into dynamic model to predict future locations.
    - Assume simple linear/polynomial motion model
  - Is reality that simple?
    - Variation in propagation delay between sources of same modality
    - Signal strength may be function of direction
    - Inter-target interference
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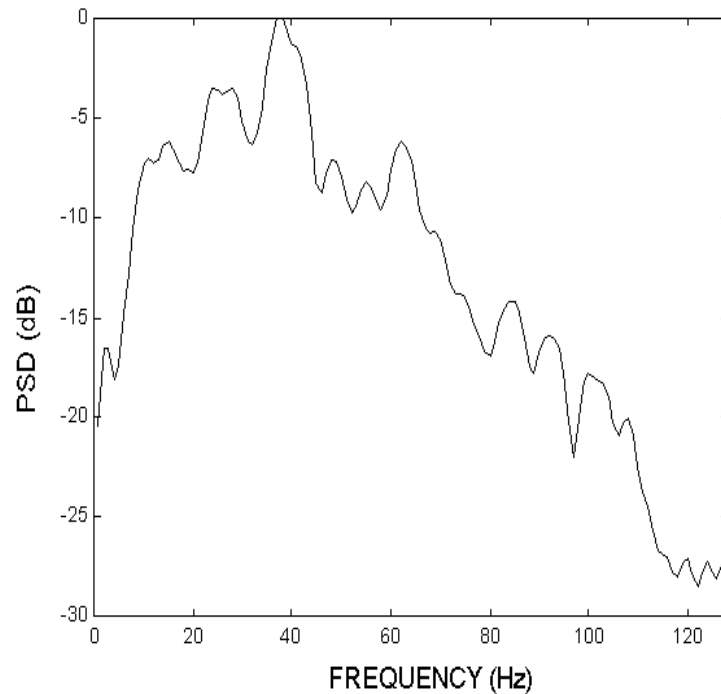
# Classification: What kind of target is this?

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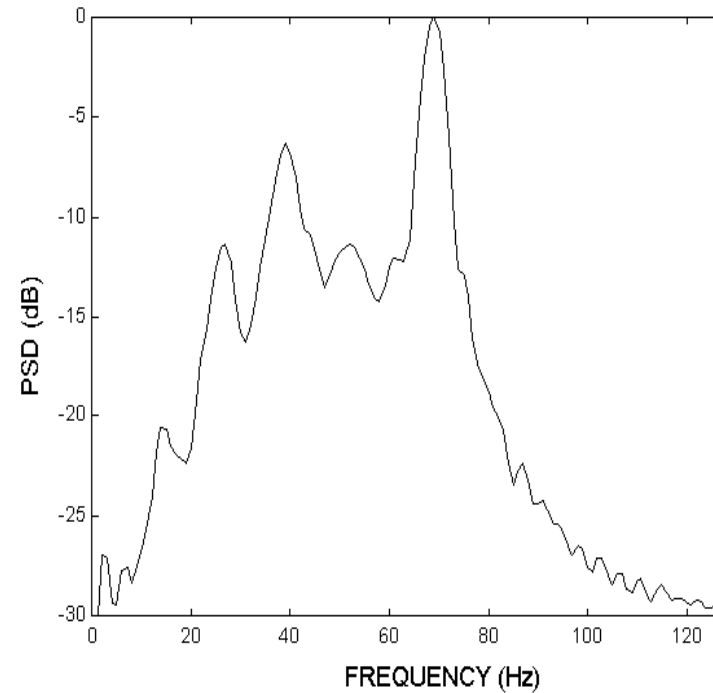
- Pick a set of features that distinguish each kind of target.
    - More specific set of features than detection!
    - Why spectral features.
      - Dominant effect consists of periodic components of vehicles. Rotating machinery (engine, gear, wheel) and tread-road impact on seismic/acoustic signatures
    - Which spectral feature?
      - FFT based Power Spectral Density
  - Compare classification algorithms
    - k- nearest neighbor (non-parametric), Max-likelihood (parametric), Support Vector Machines
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# Target Classification: Seismic PSD

## Wheeled Vehicle



## Tracked Vehicle



- ❑ Power Spectral Density plots of *different* targets by the same sensor instances
- ❑ Note the obvious differences in the prototype signatures, allowing clean separations

# Target Classification – Acoustic PSD

## Wheeled Vehicle

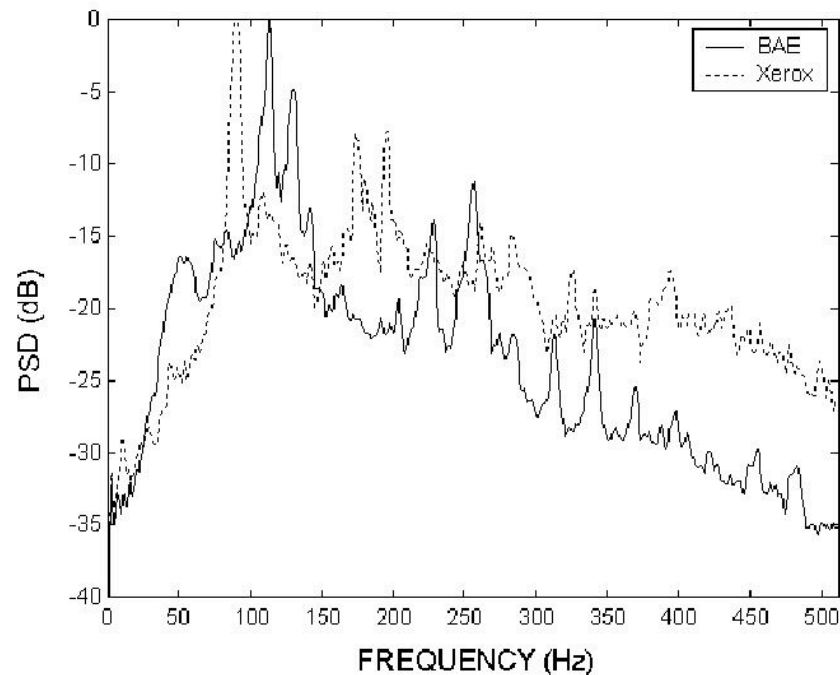


Figure 5a: Acoustic PSD of a wheeled vehicle (08020830 DW)

## Tracked Vehicle

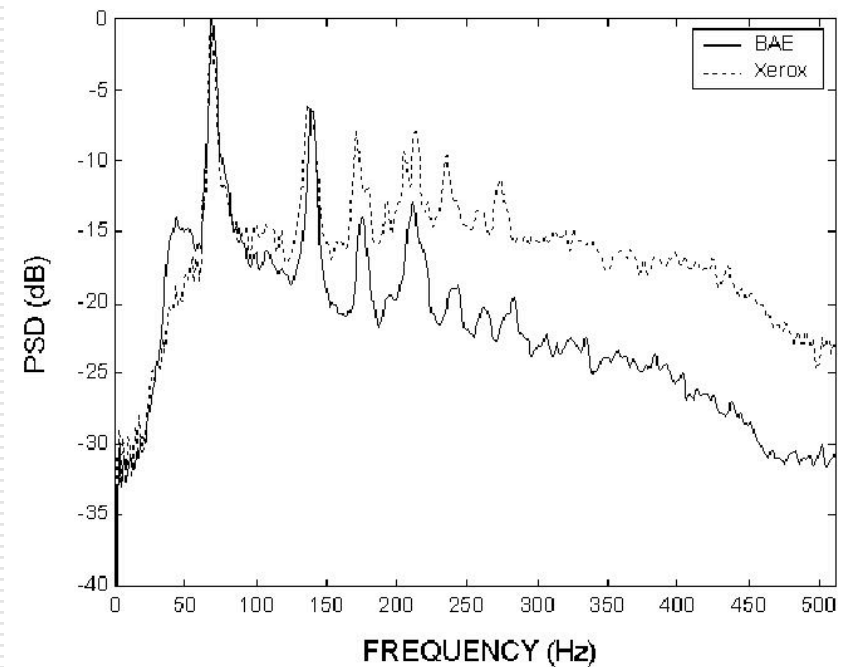


Figure 5b: Acoustic PSD of a tracked vehicle (08030800 AAV)

- Power Spectral Density plots of the *same* target by different sensor instances

# Target Classification (4) – Algorithms and Validation

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- Three classification algorithms were tested
    - k-Nearest Neighbor
    - Maximum Likelihood Classifier
    - Support Vector Machine
  - Details of the classifiers not discussed here
  - To cross-validate the performance of the classifiers
    - Available data divided into three sets: F1, F2, F3
    - Take two sets at a time for training and one for testing:
      - Experiment A – Training: F1+F2 training; Testing: F3
      - Experiment B – Training: F2+F3 training; Testing: F1
      - Experiment C – Training: F1+F3 training; Testing: F2
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# Target Classification – Acoustic Performance

- SVM demonstrates best performance
- K-NN demonstrates next best performance
- ML demonstrates poorest performance

## K-Nearest Neighbor (K = 1)

	Tracked	Wheeled
Tracked	842 (87.80%)	117 (12.20%)
Wheeled	89 (5.74%)	1461 (94.26%)

## Maximum Likelihood (Gaussian Modeling)

	Tracked	Wheeled
Tracked	779 (81.23%)	180 (18.77%)
Wheeled	171 (11.03%)	1379 (88.97%)

## SVM

	Tracked	Wheeled
Tracked	887 (92.50%)	72 (7.5%)
Wheeled	55 (3.55%)	1495 (96.45%)

# Target Classification – Seismic Performance

## K-Nearest Neighbor (K = 1)

- ❑ SVM demonstrates best performance
- ❑ K-NN demonstrates next best performance
- ❑ ML demonstrates particularly poor performance for *Wheeled Targets* (77.6% correct classification rate)

	Tracked	Wheeled
Tracked	197 (89.55%)	23 (10.45%)
Wheeled	24 (4.80%)	476 (95.2%)

## Maximum Likelihood (Gaussian Modeling)

	Tracked	Wheeled
Tracked	203 (92.27%)	17 (7.73%)
Wheeled	112 (22.4%)	388 (77.6%)

## SVM

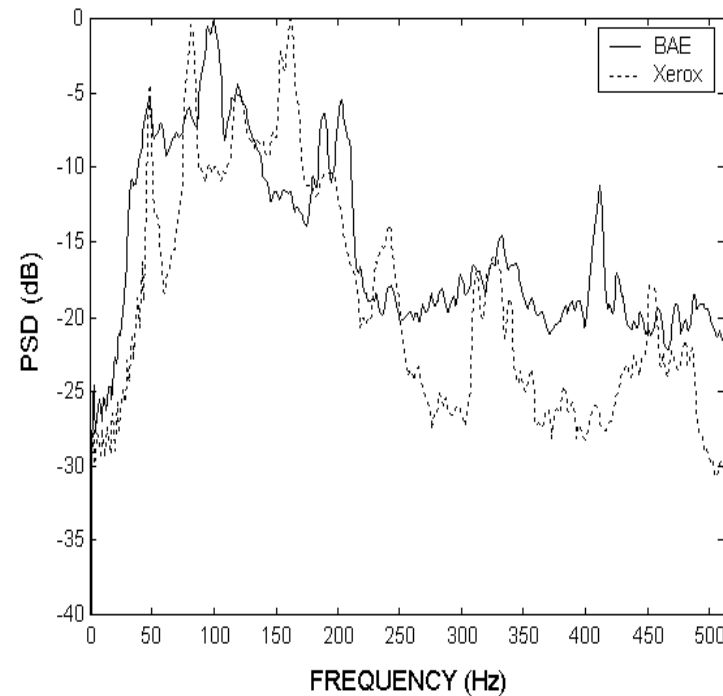
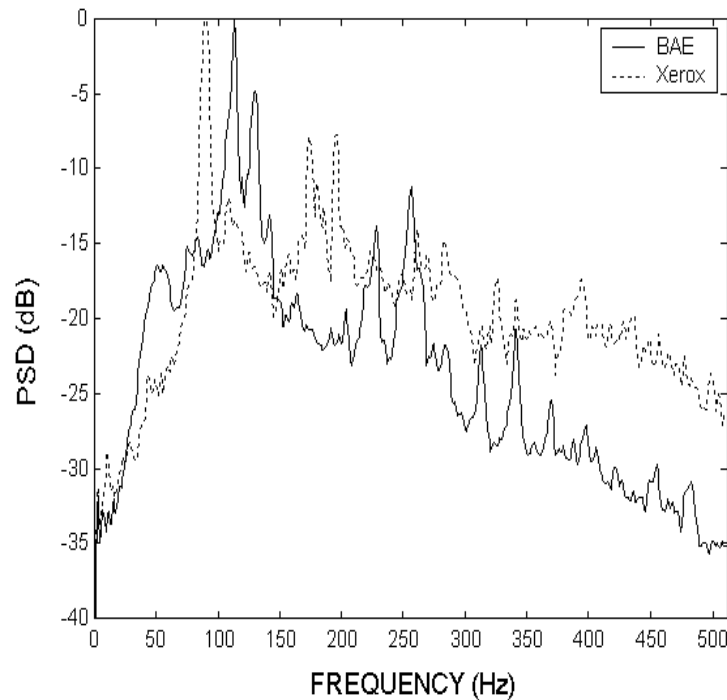
	Tracked	Wheeled
Tracked	207 (94.09%)	13 (5.91%)
Wheeled	15 (3.0%)	485 (97.0%)

# Issues and Challenges

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- Collaborative Signal Processing faces many real-world hurdles
    - Uncertainty in temporal and spatial measurements
      - Depends on accuracy of time synchronization
      - Depends on accuracy of network node localization
    - Variability in experimental conditions
      - Classifications assumes that target signatures are relatively invariant
      - Node locations and orientations may results in signature variations
      - Environmental factors may alter signals
      - These parameters may need to be included in a higher dimension feature vector at cost of increased processing
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# Challenge: Signal Characteristics Vary for same target



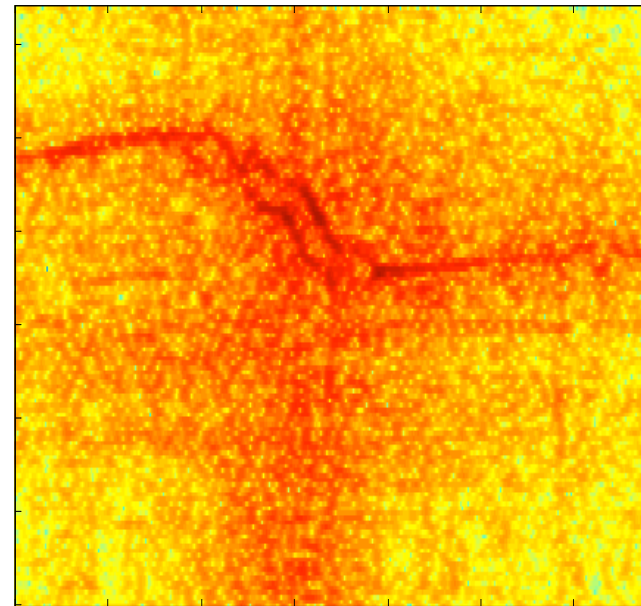
- ❑ Signatures for the *same* vehicle differ at different points in space and different sensor nodes.
  - Combine classifiers for better detection
  - Add more sensor modalities

# Challenges - Doppler Effect

- Doppler Effect on Spectral Signatures
  - Especially since acoustic and seismic have low propagation speeds.
- *Higher frequencies show greater absolute changes in frequency*

$$f = \frac{f_0}{1 - (v/v_0) \cos \alpha}$$

Frequency



Time

# Classifying Multiple Targets

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- Association Problem: Matching detections to targets
  - Very hard problem unless
    - sufficient separation in time (targets arrive at different times at the same node) OR
    - Sufficient separation in space - Targets are detected at different nodes at the same time
  - Paper focuses on the single target problem.
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# Future Research

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- Key directions
    - Move toward more collaborative algorithms
    - Extend feature space to higher dimensions
  - Intra-sensor collaboration: modal fusion
    - Combine information from multiple sensors in single node
  - Inter-sensor collaboration: centralized processing
    - Report raw time series data or statistics to a “central” node
  - Doppler-based composite hypothesis testing
    - Incorporate target velocity, CPA distance, and angle between secant and radius (vertex is target’s position)
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# Remarks

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- Paper focuses on classification. Tracking problem is mostly conceptual (although there are some interesting ideas)
  - No simulations or empirical evidence supporting single or multiple target tracking
  - Hardest problem in classification is multi-target classification
    - Overlapping signatures (disambiguation problem)
    - Tracking multiple targets
  - Max signal does not always occur at CPA
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# How to model event-based systems

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- Detection: Low-power (threshold-based)
    - P (false positive)
    - P (false negative)
  - Localization
    - Time of flight, angle of arrival, signal power
    - Location estimate + error distribution
  - Tracking
    - Use location to determine track
    - Uncertainty: location uncertainty + track uncertainty
  - Classification
    - Multiple modalities. Find distinguishing features
    - P (false positive)
    - P (false negative)
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