Fusing data from near-shore and long-range sensors in a multi-layered network

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SRI Objective and Architecture

To study and address the threat of pirated ships in the MTS being used as a dirty bomb.

Consequence Assessment

Sensor and Technology Applications in Port Security

Define the strengths and limitations of sensor technologies to detect, classify, and track vessels in, near, and approaching the urban port environment.

Long Range Technologies

Satellites, HF Radar, AIS

Near Shore Technologies

Acoustics, Electro-optics

Decision Support Methodology

Vessel categorization, threat assessment
Transportation & Security

• Purchasing Power
  – Trends and markets of the future

• Maritime Transportation System (MTS)
  – Access to worldwide markets (85% of all goods)
  – System of Systems (Bigger responsibility on the legs, i.e. loading, railroad, etc)

• Security & Resilience
  – Protected by coast guard, military, etc
  – Security vs. Operation (i.e. Containers)
Presentation Outline

• Technology Overview
  – Near Shore Systems:
    • Acoustics and Electro-Optics
  – Long Range Systems
    • Satellites, AIS, HF Radar
• Data Collection & Layered Architecture
• Tracking Examples
• Decision Support
• Acoustic integration for Hawai’i (Oahu)
  → My current research & plans

Stevens’ Research Vessel,
RV Savitsky on Hudson River
Acoustic Data Collection & Processing

In Water System

**SPADES**
Stevens Passive Acoustic Detection System

Data from hydrophone acquired and recorded

Data pre-processed in underwater system and transmitted digitally

SPADES GUI

Spectral Analysis

Cross-Correlation Analysis

Signature Analysis

Frequency (Hz)

Time (s)

Boat Signal

Cross-Correlogram

Circular Cross-Correlation

Land based system

Spectrogram

Demon Spectrum
DEMONT Analysis

- **Detection of Envelope Modulation on Noise**
- Allows for classification by demodulating vessel specific noise
- Demonogram (top) shows how the spectral density of a vessel characteristic signal varies with time
- Demon Spectrum (bottom) shows the time averaged (60 s) representation of a vessels signal in the frequency domain

Demonogram and DEMON Spectrum
Infrared vs. High-resolution video

Video taken on July 4, 2011 from Maritime Security Laboratory

**Infrared Image**
- Thermal image does not change
- Vessels can be tracked independently of light source

**Optical Image**
- Vessels are hard to track as natural light decreases (use their self lightening)
- Vessels are impossible to track w/o own light
Satellites - Introduction

- Early detection
  - Low to high resolutions
  - Monitor environmental conditions
  - Limited availability
  - Required trained personnel to operate
  - High operational cost
  - Processing time depends on orbit, post-processing, and image download time

SAR image of NJ, Manhattan and Brooklyn
Types of Satellite Imaging

Optical
- Uses visible and infrared light
- Passive detection
- No image distortion

Synthetic Aperture Radar (SAR)
- Uses radio waves
- Active detection
- Higher resolution images, covering larger areas
- Flight path simulates large antenna (phase corrected signal summation)
- Images are distorted
- Can look through clouds
- Study Internal waves
- Thermal expansion of buildings
Satellite image comparison: Optical vs. SAR

EROS-B at 18:57:00 GMT on 7/11/2011
- Clouds covering bridge
- Wakes of vessels barely visible

- No clouds
- Wakes of vessels visible
- Buildings leaning to right
Automatic Identification System (AIS)

- Tracks time and location of vessels
- Provides name, type of vessel, MMSI #, country of origin
- Class A and Class B
- Stevens, Rutgers, and Coast Guard receivers
- Compatible with Google Earth
- Only effective when AIS transmitter is turned on in vessels
Ship Identification-AIS

- Comparison of SAR Satellite image and AIS Google overlay
- SAR image taken by TerraSAR-X on 10:56:19 GMT on 7/12/2011
- Vessel's Details
  - Speed recorded (Max): 10.2 knots
  - Call Sign: WDD5445

Source: marinetracking.com
Vessel Detection
- Detection range: 0 to 70 km
- 3 to 30 MHz or 100 - 10 m wavelength
- Detects vessels trajectory, distance and velocity
- Cannot characterize type of vessel
- Effective in fog and rain
- Requires surface disturbance
HF Radar - Introduction

Cross Spectral Image
- Three plots show 2 directional loops and monopole
- Doppler spectrum determines vessels direction and speed
- Bragg Waves: ⭐ A measure of radar signals scattered by waves

Range Cell Image
- 95 range cells with each range cell being ~3 km long
- Three colors represent three loops, or antennae on the radar
Layered Architecture

Satellite Overlay

RADAR coverage

HF Radar coverage

SPADES coverage

HD Camera coverage

- SPADES
  - max detection range: 2.5 km
  - usual detection range: 1.2 km

- Coverage hole in the layer between SPADES and HF Radar
Data Collection Process

- AIS
- RADAR
- SPADES
- HF Radar
- Satellite

HF Radar Map (Google Earth)

AIS, Radar, and Spades Map

Record and review

Optical and IR Camera

NYHOPS
Example of acoustic layered architecture

- **AIS ID:** 305535000
  - **Ship Type:** Cargo
  - **Length x Breadth:** 190 m X 25 m
  - **Flag:** Antigua Barbuda [AG]

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<th>Time (GMT)</th>
<th>Distance* (m)</th>
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<td>Video detection</td>
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</table>

*Distance measured from SPADES
Tracking Redundancy: Pacific Huron

Ferry Signal

Pacific Huron

SPADES

Video

DemodSpectrum Ch0

22:49:00
Detection Distances

- Acoustic detection depends on several factors
  - background noise (bridges, rain)
  - interferences from other targets (coherent noise)
- Maximum detection distance for SPADES bounded by two ferry terminals (2.5 km N, 750 m S)

Carnival Miracle: Cruise Ship
Detection: 1200 m, Loss: 1200 m

Thomas D. Witte: Tug Boat
Detection: 550 m, Loss 1000 m

Small Pleasure Craft
Detection: 450 m, Loss 800 m

Robert Fulton: NY Ferry
Max Detection Distance: 2500 m
# Acoustic Classification

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Fundamental Frequency range [Hz]</th>
<th>1st Harmonic [Hz]</th>
<th>2nd Harmonic [Hz]</th>
<th>3rd Harmonic [Hz]</th>
<th>Other frequency [Hz]</th>
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<td>n/a</td>
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<td>79</td>
<td>105</td>
<td>n/a</td>
</tr>
</tbody>
</table>

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[Images showing Savitzky and Tugboat graphs]
Near Shore Technologies

• Conclusions
  – **Acoustics** is a reliable system in tracking vessels of interest (real time!) in the absence of dominant noise (i.e. other vessels or rain)
  – Successful in detection, tracking and classification but more complicated (changing environment)
  – Additional technologies (underwater optics, gliders, floats..)
  – **Electro Optics** can be used as detection and validation tool (requires operator)
  – IR limitations have to be considered (reflectivity & emissivity)
Long Range Tracking: HF Radar

Cross-spectra, 10:10:59 GMT on 7/19/2011

Ship Detection GUI, 10:20:00 GMT to 11:10:00 GMT on 7/19/2011
Long Range Tracking: AIS and Satellite (SAR)

AIS data overlaid onto Google Earth, 10:13:45 GMT on 7/19/2011

Satellite image taken by COSMO-SkyMed, 10:13:06 GMT on 7/19/2011

Joan Moran (MMSI # 368669000)

Miss Gill (MMSI# 367122680)
Long Range Tracking: Complimenting HF Radar with AIS

Cross-spectra, 18:24:58 GMT on 7/26/2011

AIS data overlaid onto Google Earth, 18:26:59 GMT on 7/26/2011
Long Range Technologies

• Conclusions
  – Best used in a layered approach
  – Successful in detection, not identification
  – Good for port security because:
    • Satellite gives a large overview of the area
    • Good tools to display post effects (i.e. oil spill)
    • HF Radar can see over the horizon
  – HF Radar
    • Best used for surface currents (Search and Rescue)
    • Hard to clearly detect vessels
    • Individual stations can be synched to a network
Multisource Data Interpretation:

How do you get from this…

Characteristic Frequency + Blurry Camera + HF Radar Screen

HF Radar, Speed and Range + ?

…to This?

Vessel Specifics
<table>
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<th>Classification</th>
<th>Wake Description</th>
<th>Fundamental Freq(1)</th>
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<tbody>
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<td>88-97</td>
</tr>
</tbody>
</table>

### Vessel Info:
- **Length**: 20-50’
- **Draft**: <4’
- **Beam**: 6’

### Suspicious:
- **Should It be Broadcasting AIS?**
- **Is it Where Expected?**
- **Is it Acting as Expected?**

### Contact:
- **Fundamental Frequency**: 88Hz
MAGELLO GUI

- http://www.stevens.edu/csrmagello/
Acoustic Network in Hawaii

• Real time data collection and processing
  – Simplicity & robustness

• Export processed data to a GUI (.kml)
  – Simple and intuitive display for layering technologies

• Interaction with other technologies:
  – Record position and signature \( \rightarrow \) provide acoustically relevant information about a source
  – complete time history
Next Steps

• Design and conduct an acoustic experiment on the south shore of Oahu this Fall
  – 10+ hydrophones, arranged in 2-3 clusters with both TDOA and Beamforming capability
  – Record Diver Signatures
    • Diver detection (breathing rate & frequency band)
    • Extraction of equipment specific frequencies
  – Vessel of opportunity / Diver tracking
    • Optimize with custom weights / UKF
Thank you for your time!

Are there any questions?

This material is based upon work supported by the U.S. Department of Homeland Security under Grand Award Number 2008-ST-061-ML0002. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.
Monitoring Early Vessel Traffic

Long Range detection and tracking within major shipping lanes might be accomplished with 4 hydrophones.
## DEMON Spectra Classification

### Circle Line Cruise Ship

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Fundamental Frequency range</th>
<th>1st Harmonic</th>
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<th>3rd Harmonic</th>
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</table>
Stability of Demonogram

Abraham Lincoln Ferry 7/11 19:04
Savitsky 7/11 11:51

Douglas B Guarin Ferry 6/30 20:34
Savitsky 7/11 11:59
Engine Speed Effects on DEMON Signature

DEMON analysis gives us a signal which is dominated by the engine and propellers.

As the engine speed changes, the DEMON spectra will as well.

Signatures show that the vessel dependent frequencies change proportionally when the engine speed changes.

Unknown Boat 6/30 18:57.
Peaks change by a factor of 0.72

Unknown Boat 6/30 18:42.
Peaks change by a factor of 1.08
## Appendix 1: Acoustic Classification

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# Appendix 2: Stability of Savitsky Signal

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<th>Savitsky</th>
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### Appendix 3: Engine Speed Effects

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Introducing Digital Image Processing

• Set of computational techniques for analyzing, enhancing, compressing and reconstructing images

• Applications:
  – Image Subtraction: pixel by pixel intensity subtraction between two images to form a better contrast image with the potential target
  – Image Overlay: Alignment of overlapping HR and IR images to construct one seamless composite image with more detail
  – Noise and glare reduction
  – Edge and corner detection
Example Image Overlay

Original HR Image

Overlaying Image

Original IR image
Image Processing for Detecting Multiple Targets
Image Subtraction

**Goal:** contrast enhancement (for edge detection)

Image of interest (1) is subtracted from a time averaged reference image.

Resulting image (2) is the contrast enhanced image
  → eases operator decision
  → further processing
Image Processing

• Conclusions
  • Image subtraction was established as a viable surveillance technology
  • You can detect things better & nice for further processing
  • Suggests automation

• Recommendations
  • Create a database of background images sorted by significant changes in the environment
  • Fully automate the algorithm so it continually analyzes IR images
  • Make the algorithm do successful image vessel classification
  • Create a fully-functional GUI that could be integrated into a surveillance system such as BOOM
IR Imaging Overview

• All objects radiate thermal energy
  – As the temperature increases, the amount of thermal energy increases while the **peak wavelength** of the radiated energy decreases

• IR cameras detect radiated energy, **NOT Temperature**
  – Heat energy is emitted by the object so no light or heat source is needed
  – Emissivity is a characteristic of the material. Two objects at the **same temperature** can emit a different amount of energy and thus appear different on an IR image

Aluminum emissivity of 0.1,
Electrical tape emissivity of 0.95.

IR represents the wavelengths slightly longer than visible
# Satellite Flyovers

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<th>Date</th>
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<th>Type</th>
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<td>SAR</td>
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<tr>
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<td>11:13:25</td>
<td>TerraSAR-X</td>
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</table>
SAR: Image Distortion

- Beam reaches top of target before it reaches its bottom
- Image appears compressed
Ship Identification - Wakes

- Large vessels are easy to see
Types of Satellite Imaging

• Optical
  – Passive
  – Uses visible and Infra-Red light

• Synthetic Aperture Radar (SAR)
  – Active
  – Flight path simulates large
Simulation Results - GPS Tracking route

- Pin ups represent Savitzky’s positions at time of Satellite images
- Routes also confirmed with SPADES and Video

- Savitsky confirmed with satellite image
- Savitsky not confirmed on satellite image
- Savitsky’s explosion site (confirmed)
Acoustic detection distance: 550 m at 22:48:00 GMT
Acoustics loses contact: 460 m at 22:50:50 GMT due to ferry noise from the north
Long Range Flow Chart

AIS
- Transas AIS
- USCG AIS
- Rutgers AIS

CODAR
- Microwave signals hit water surface and ships
- Surface Velocities and Vessel Detection
- Seabright Website
- Range Cells
- Spectral Images

Tools for viewing raw data
Tools for interpreting processed data

Google Earth
Ship Detection GUI

Bearing, Velocity and Range
SNR
Filters
Threshold

Manipulating SNR that can be viewed by tools
**Threat ID: Check For Normal Behavior**

### Classification

<table>
<thead>
<tr>
<th>Classification</th>
<th>PAX</th>
<th>LOA</th>
<th>Gross Tons (tons)</th>
<th>Top Speed (Kts)</th>
<th>Draft (FT)</th>
<th>Beam (FT)</th>
<th>Height</th>
<th>MR (1-10)</th>
<th>Payload (Tons)</th>
<th>AIS Required? (Y/N)</th>
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</table>

### Tracking/Detected Parameters

- **Classification**: Container Large,
- **Areas of Operations**: Upper Bay, Red Hook or Port E.
- **Expected areas of Operations**: Upper Bay, Red Hook or Port E.
Bay and Oceanographic Observation Management System (BOOM)

Integration of sensor displays

Law enforcement official

BOOM

DETECTION SYSTEMS

Acoustic
HD cameras
CODAR
RADAR

Data Fusion

Laboratory setting

Single Integrated display
User Information Tools

How do you get from this…

Demon Spectrum + Blurry Camera Image + HF Radar Screen

HF Radar – Speed and Range

…to This?
Bay and Oceanographic Observation Management System (BOOM)

Integration of sensor displays

- Acoustic HD cameras
- CODA R
- RADA R

DETECTION SYSTEMS

Data Fusion

Law enforcement official

Laboratory setting

Single Integrated display
Acoustic Data Collection and Processing
Stevens Passive Acoustic Detection System (SPADES)

Passive Acoustic Detection with four hydrophones

Data from hydrophone acquired and recorded

Data pre-processed in underwater system and transmitted digitally

SPADES GUI

Spectral Analysis

Cross-Correlation Analysis

In Water System

Land based system

Frequency (Hz)

Time (s)

Boat Signal
Who Uses Sensor Networks?

Law Enforcement: United States Coast Guard

Problem: Vessels without AIS

Needs: 
- Tracking
- ID or Classification

Emergency Response: OEM & First Responders

Problem: No Modeling Input Data

Needs: 
- Visual Information
- Vessel Information

CLASSIFICATION
Contact ID and Assessment Process

Vessels With AIS

NOAD Expected?

YES

Contact USCG to confirm NOAD

NO

Vessels With AIS

AIS?

YES

Use T&D Table to attempt to classify

NO

Continue to Watch and attempt classification

Classify Vessels Without AIS

Contact!

Threat ID

Any Flags?

YES

Flag 1

Classified: AIS Expected?

NO

Flag 2

Expected AOA?

NO

Flag 3

Behavior Expected?

NO

In Exclusion Zone

NO

No Threat Detected

Continue Monitoring in Background

YES

Notify USCG

NO

Notify USCG
To study and address the threat of pirated ships in the MTS being used as a weapon of terror

Define the strengths and limitations of sensor technologies to detect, classify, and track vessels in, near, and approaching the urban port environment

- **Satellites, HF Radar, AIS**
- **Acoustics, Electro-optics**
- **Vessel categorization, threat assessment**
BOOM!: Interactive Bay and Oceanographic Observation Management System

- AIS
- SPADES
- NYHOPS
- MACOORA
- RADAR
- Satellite
- Coverage Zones
- Live Feeds