Fusion of acoustic measurements with video surveillance for estuarine threat detection

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ABSTRACT

Stevens Institute of Technology has established a research laboratory environment in support of the U.S. Navy in the area of Anti-Terrorism and Force Protection. Called the Maritime Security Laboratory, or MSL, it provides the capabilities of experimental research to enable development of novel methods of threat detection in the realistic environment of the Hudson River Estuary. In MSL, this is done through a multi-modal interdisciplinary approach. In this paper, underwater acoustic measurements and video surveillance are combined. Stevens' researchers have developed a specialized prototype video system to identify, video-capture, and map surface ships in a sector of the estuary. The combination of acoustic noise with video data for different kinds of ships in Hudson River enabled estimation of sound attenuation in a wide frequency band. Also, it enabled the collection of a noise library of various ships that can be used for ship classification by passive acoustic methods. Acoustics and video can be used to determine a ship's position. This knowledge can be used for ship noise suppression in hydrophone arrays in underwater threat detection. Preliminary experimental results of position determination are presented in the paper.

Keywords: Passive acoustic detection, ship noise, video surveillance, cross-correlation, underwater sound attenuation

1. INTRODUCTION

In 2006, Stevens Institute of Technology established a research laboratory environment in support of the U.S. Navy in the area of Anti-Terrorism and Force Protection (AT/FP). Called the Maritime Security Laboratory, or MSL, it provides the capabilities of experimental verification of AT/FP research in the realistic environment of the Hudson River Estuary. The laboratory infrastructure is described briefly in Section 2.

The goals of MSL are:

- To continuously advance the state-of-the art in technologies key to maritime security in an estuarine environment
- To develop transportable intruder detection prototypes embodying results of new maritime security research, deployable to harbors around the world for military and commercial applications
- To become a national resource in the maritime security for the US Navy and also for the domestic security, maritime industry, and natural hazards mitigation communities.
- To develop a work force for the future through extensive involvement and education of students, post-doctoral, and academic and research faculty in the area of maritime security.

Initially, the focus of MSL was on threats posed by surface and subsurface intruders including SCUBA divers and small boats by using passive acoustic techniques.[1,2] Using these initial capabilities, MSL investigated the set of acoustic parameters fundamental to underwater acoustic threat detection including: diver acoustic signature, acoustic transmission loss, and acoustic environmental noise. The initial infrastructure has since been extended to include computer optic and infrared vision capabilities, and to enhance acoustic experiments by combining them with these capabilities.

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These integrated capabilities have enabled experiments in determining the positions and trajectory of surface traffic, which may be both a sources of acoustic noise in intruder detection as well as possible targets themselves. This knowledge can be used for measurements of acoustic noise of various ships and their classification, determination of sound attenuation in a wide frequency band, and the development and testing of methods of passive acoustic triangulation and location of sources of sounds. Interest in the joint use of acoustic and optical surveillance is also discussed in connection with a prototype Expeditionary Integrated Swimmer Defense System that was tested in September, 2007[3] and possible implementation of optical surveillance in an Integrated Anti-Swimmer System for US Cost Guard.[4] These systems, however, utilize active SONAR, while we concentrated on passive acoustic detection methods.

This paper describes some new opportunities for joint passive acoustic/computer vision surveillance. The MSL infrastructure used for our tests is described in Section 2. Section 3 describes the results of joint acoustic/computer vision experiments. Next steps in the evolution of the MSL architecture involving the development of a multi-modal maritime intruder detection system are discussed in Section 4.

2. THE MARITIME SECURITY LABORATORY

Part of the uniqueness of Stevens' Maritime Security Laboratory is its location on the Hudson River tidal estuary, which is a key waterway that defines the Port of New York/New Jersey, one of the busiest harbors in the U.S. From a scientific perspective, this harbor embodies a high degree of complexity due to variability of the current, salinity, temperature, winds, turbidity, as well as man-made factors including ambient noise due to surface and air traffic, construction noise, and various forms of electromagnetic radiation. All of these enter into the analysis of above and below surface threats.

Hence the estuary itself is an integral part of the laboratory. As discussed above, the estuary is equipped with instrumentation to collect weather and environmental data, and through modeling, to predict their characteristics. For the actual MSL execution of experiments, the test site has been chosen based on its scientific characteristics and its accessibility both by radio communications and by safety considerations. The test site is shown in Figure 1. The MSL research vessels are shown in Figure 2. The larger boat is the RV Savitsky. It is specially constructed and fitted out for maritime research purposes. Towards the stern is an A-frame for loading large and heavy items onto and off of the boat. Radio antennas are affixed to the mast to transmit real-time experiment data to the MSL Visualization and Analysis Center (VAC). The smaller boat, the Phoenix, is a support boat. It is used to deploy sensors while they are cabled to the Savitsky. It is also used to deploy remote instrumentation, divers, and provide for safety. In addition, it is used as the point of radiation in experiments involving acoustic propagation between two points and measurements of temporal variability of acoustic field.

Figure 1. Test site in the Hudson River.

Figure 2. MSL research vessels (Savitsky (left) and Phoenix).

The MSL laboratory and its key components are shown in Figure 3. Starting at the left, various sensors are deployed at the test sites. Depending on the experiment, these may include hydrophones, sound emitters, CTD's (for conductivity, temperature, and depth), Acoustic Doppler Current Profilers, inclinometers (to measure the roll of the boat), various radio link instrumentation, and so forth. Experiment-specific instruments are cabled to an on-board boat computer although future experiments will involve direct wireless connectivity from the sensors, as well. This will be done to both simplify the experimental setup on the water, as well as to facilitate research into areas such as ad hoc wireless maritime networks and larger physical areas.

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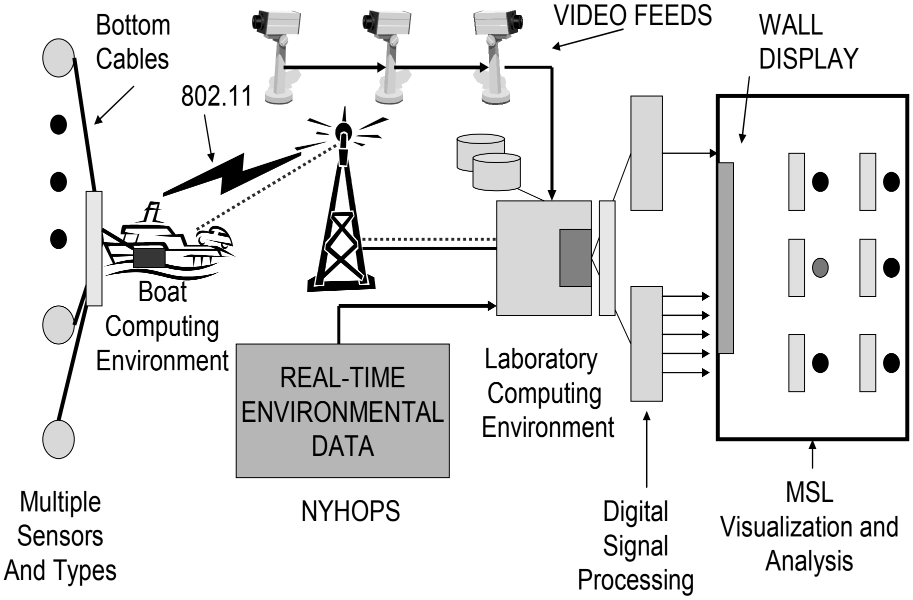


Figure 3. The MSL Laboratory Infrastructure.

Communications with the boat is accomplished with an IEEE 802.11 (WiFi) radio link. This link is used to enable real-time data to be transmitted to the Visualization and Analysis Center (VAC). This enables experiments to be controlled from the VAC, in terms of when and how long data is recorded. Perhaps most importantly, it provides Data Quality Assurance, to assure that at the end of the day, good data has been collected. Another important application of the radio link is to maintain real-time communication with the boat crew during experiments. This is accomplished by establishing a chat line with the boat, and is critical to the logistics and administration of experiments. The radio link is connected to the VAC over the campus network.

The Visualization and Analysis Center has several major purposes:

- To provide the capability to administer and control experiments, whether on the boat, or elsewhere
- To ensure data quality assurance during experiments
- To enable the ability to reconfigure experiments in response to the data received. (This capability will become more significant as we undertake experiments in adaptive learning)
- To provide an environment for research, algorithm development, and laboratory infrastructure improvements
- To provide a demonstration capability for key stakeholders and potential customers and users.

In 2007, the Stevens MSL VAC was established in its permanent location in the Babbio Center overlooking the Hudson River. The display system of VAC is shown in Fig. 4. The VAC location has a terrace overlooking the River. This facilitates experiments with various types of video and infrared cameras as shown in Fig. 5.

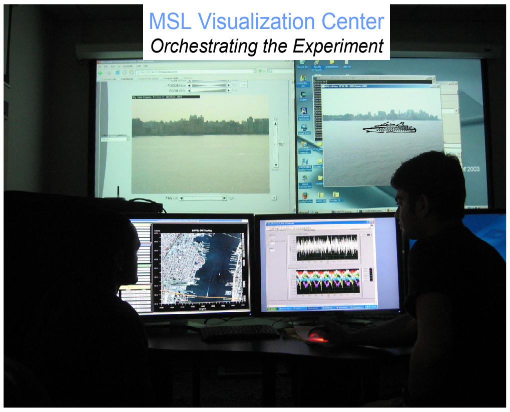


Figure 4. Display of MSL VAC.

Figure 5. Imaging experiments from the Babbio Center Patio.

In addition to real-time data feeds into the VAC, six video cameras have been deployed to provide real-time visual observation of experiments, as well to provide a video data source to automatically collect data, and to analyze surface and low flying aircraft traffic, as well as intruder activity. As described in Section 4, a Surface Traffic Tracking System has been developed by Stevens' scientists utilizing these video cameras, which automatically detects the entry of surface craft into a calibrated sector of the estuary. Utilizing this system, the position, bearing, and velocity of traffic can be automatically detected and recorded. Path information on detected traffic is projected onto a Google map as well as stored in a data base. By observing the acoustic signature of passing craft via hydrophones, and correlating that with the position information recorded by the Tracker, one can determine, for example, the transmission loss of the path between the source (the passing craft) and the receiver (the hydrophone), as described in Section 5. Furthermore, time delay analysis can be used in a set of hydrophones to determine the bearing or location of a target. Then the cameras, visible or infrared, can orient themselves toward the target for a better look. Early results in this area are given in Section 4.

The intruder detection problem is complicated by the high degree of spatial and temporal variation of an estuary due to tides, winds, currents, precipitation, traffic, power plants, and so forth. The complexity of this environment requires that real data be used in its modeling. Such data-driven mathematical models have been built by Stevens and are used to predict oceanic and atmospheric environmental factors. The model, the Stevens New York Harbor Observation and Prediction System (NYHOPS), can be found at http://hudson.dl.stevens-tech.edu/NYHOPS/.The interrelationship between NYHOPS predictions of acoustic parameters and MSL experimental measurements was studied over a 12 hour tidal cycle.

3. BRIEF OVERVIEW OF PRIOR MSL ACOUSTIC EXPERIMENTS

Previous acoustic experiments conducted by MSL include measurements of the acoustic signature of SCUBA divers, acoustic estuarine transmission loss, and ambient noise. MSL has a variety of hydrophones that were used for these experiments. We frequently used ITC 6050 hydrophones produced by International Transducer Corporation due to their high sensitivity and lower noise level in the frequency band up to 100 kHz.

In our tests, hydrophones were placed at various heights in the water column, or on the river bottom on stands. All deployed hydrophones were connected by cable to the on-board computer for data processing and storage. The signals from the hydrophones were amplified and filtered in the frequency band 5- 95 kHz. This filtering was applied for suppression of the high acoustic noise level in the low frequency band, which limits the dynamic range of measurements and for elimination of spurious aliasing signals produced by electromagnetic noise at frequencies above 100 kHz. The amplified and filtered signals were digitized by an 8 channel data acquisition system and recorded. The sampling rate was 200 kS/s, which allows recording of signals with bandwidth up to 100 kHz. The boat computer was wirelessly connected with MSL Visualization and Analysis Center, so all information displayed on the boat computer was displayed simultaneously in VAC. This allowed scientists in the VAC to control the experiments.

The acoustic propagation experiments were conducted by radiating an acoustic wave between a transmitter and receiver. The radiating wave was generated by a calibrated reversible Reson hydrophone. The following experiments were conducted in this way:

1. Measurements of transmission loss in a wide frequency band (20-100 kHz) in Hudson River were carried out, including the effects of tidal variation.
2. Determination of the shallow channel impulse response using correlation techniques. The measured impulse response is used by Stevens' researchers for estimation and prediction of underwater acoustic communication systems performance.
3. Measurement of the acoustic signature of SCUBA divers using various SCUBA equipment. The comparison of diver acoustic signal with a signal produced by the calibrated emitter allowed the estimation of the diver source level.
4. Ambient acoustic noise was measured in various environmental conditions and for water traffic. The joint application of acoustic measurements and video surveillance allows determination of acoustic noise produced various kinds of ships and application of ship noise for acoustic attenuation measurements. Some of these results are presented in the current paper and the paper. [5]
5. The received data for diver source level, acoustic attenuation and noise were applied for estimation of a diver detection distance and results are presented in our other paper of this volume.

4. VIDEO SURVEILLANCE SYSTEM AND METHODS OF WATER TRAFFIC MAPPING

Stevens is developing a two-layer context-focused architecture for video tracking and surveillance. The video surveillance system is combined with acoustic sensors. The two layer video surveillance and tracking concept (Figure 6) is based on a sparse array of cameras and is designed to:

- Track multiple targets and events
- Focus and zoom in on a number of specific events and objects.

The first (context) layer agents are called the wide area surveillance system (WASS) agents. Each WASS agent uses a single camera to monitor a sector of up to 180 degrees angular opening and radius up to 8.5 miles; the WASS system is designed to identify and track automatically multiple maneuvering (possibly overlapping) targets. The second (focus) layer agents are narrow-field-of-view video tracking agents called auto-servo-focused-tracker (ASFT) agents. Each WASS agent can spawn and interact with multiple instances ASFT agents. The ASFT agents are capable of focusing on a single target and following it with automatic pan/tilt/zoom.

Our system combines robust routines for detecting moving objects in the real-time video stream by combining temporal differencing, template tracking of automatically generated templates, dynamic construction and update of semantic object and behavior categories, and robust image rectification and geo-referencing. Because of the long tracking ranges, the real-time requirement, and the necessity to keep track of targets of vastly different sizes in a cluttered environment, our system puts heavier emphasis on kinematics and semantic models than on pattern recognition based on image-based bags of features.

We use adaptive background subtraction as the basis of our detection and tracking system. At the pixel level we exploit running average pixel value

$$\tilde{p}_t = \frac{1}{N}\sum_{k=1}^{N} p_{t-k}$$

where the learning rate N is adapted to the scene and video type. This simple background accumulation is chosen to maintain real-time performance. The strongest factor determining the learning rate is the need to factor out quasi periodic water wave clutter. We monitor the global frame variation to compensate for sudden global environment changes and to perform image stabilization. Based on our experimental experience we rely most heavily on re-initializing the background history. The threshold level used for motion segmentation is a learned parameter based on the scene type. The motion segmentation stage identifies moving features with the connected components of the eroded-dilated threshold image identify moving features. A multi-component history system and Kalman filters are used to perform data association, target detection and tracking. The attributes identifying a target include kinematics parameters, appearance features, target size, center of mass location, and lifetime length. The semantic reasoning subsystem uses these attributes to de-clutter the scene – removing water waves, water reflections, camera motion artifacts, motions outside area of interest (for example vehicle motion along the driveways when the system is tracking ships and small boats). To deal with overlapping targets our system exploits robust methods to detect and handle target overlaps.

The detection of overlaps is based on analysis of the possible behaviors causing target overlaps. A possible overlap leads to significant increase in the motions detected by the motion segmentation stage. This cue is detected by monitoring sized dynamics of the viable objects. The target size dynamics are combined with methods to predict the events when viable targets come close to each other. The measures used to measure proximity combine the distance between the objects centers of mass and normalization accounting for the object size. Once an overlap is detected the system exploits the kinematics models the life length and the rest of the target attributes keep track of targets that could be temporarily occluded by other foreground targets.

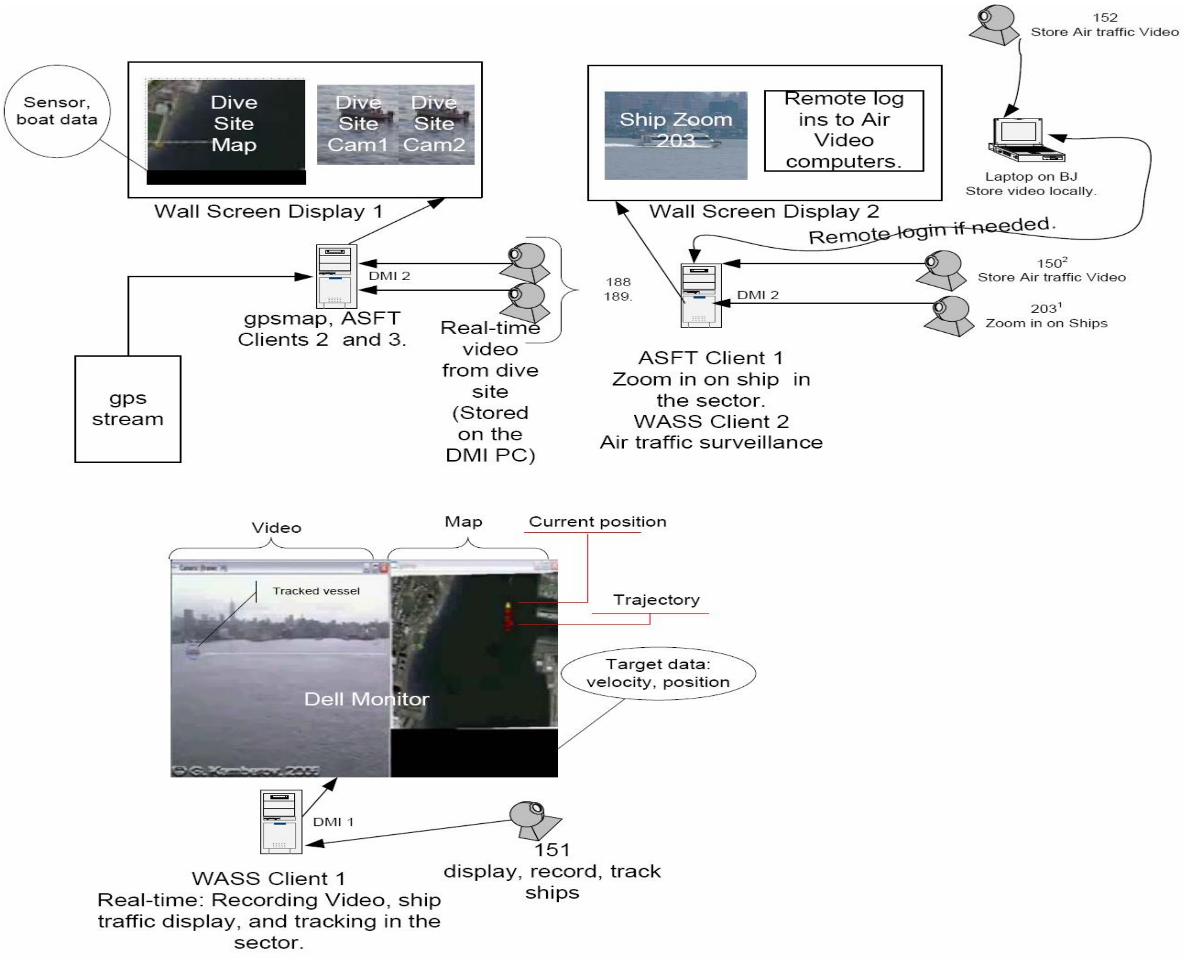
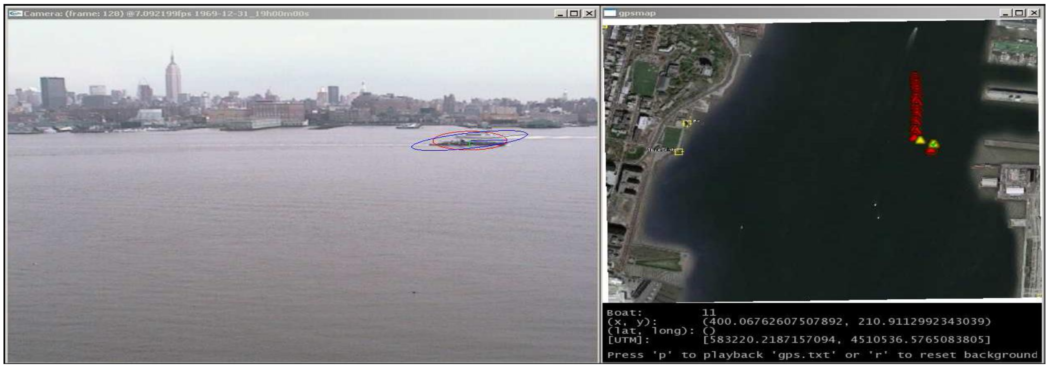


Figure 6: MSL Video Surveillance System. Here we are running two instances of the WASS. WASS Client-1 monitors boat traffic in a predefined sector and WASS Client-2 monitors aerial traffic over the river sector.

To estimate the geographic coordinates of the detected and tracked targets we rectify the frames by warping them to pre-rectified and geo-referenced frame sequences tracking a survey vessel equipped with a high precision GPS unit.

Figure 7 shows a screenshot from The Stevens Wide Area Surveillance System (WASS). It detects and tracks boats on the Hudson River. The system localizes boats in the 2D image plane (left viewport) but also computes the world co-ordinates of tracked boats and plots them on a geo-referenced satellite image map of the river (right view-port). Using predictive trajectory extrapolation and a (learned) behavior model, we are able to track two boats even when one of them occludes the other in passing (see above). In the right hand image, red triangles denote the recent history of motion whereas yellow triangles denote the current position of each boat/target.



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Boat:          11
(x, y):        (400.06762607507892, 210.9112992343039)
(lat, long):   ()
[UTM]:         [583220.2187157094, 4510536.5765083805]
Press 'p' to playback 'gps.txt' or 'r' to reset background
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Fig 7. Screenshot from the Stevens Wide Area Surveillance System.

5. CROSS-CORRELATION OF ACOUSTIC SIGNALS FOR DERECTION-FINDING AND SOURCE LOCALIZATION

A commonly used direction-finding method is based on cross-correlation techniques for estimation of the relative time delay between signals arriving at different hydrophones. This method is used, for example, for analysis of whale signals and their location.[6-10] A similar technique was applied in our test in the Hudson River for measurements of the time delay between acoustic signals generated by moving ships. Video recording and mapping of ship positions allowed us to compare results of acoustic measurements with video-based ship positions.

Water traffic noise measurements were conducted near the Stevens campus at Castle Point in the Hudson River estuary, as shown in Figure 8. The description of acoustic and video methods is given in previous sections of this paper. In this section, we present results of the cross-correlation of acoustic signals recorded by two Reson TC4014 hydrophones placed off of the Stevens research vessel *Savitsky* with distance of 7.5 meters between them. Figure 8 shows simplified configuration of the test.

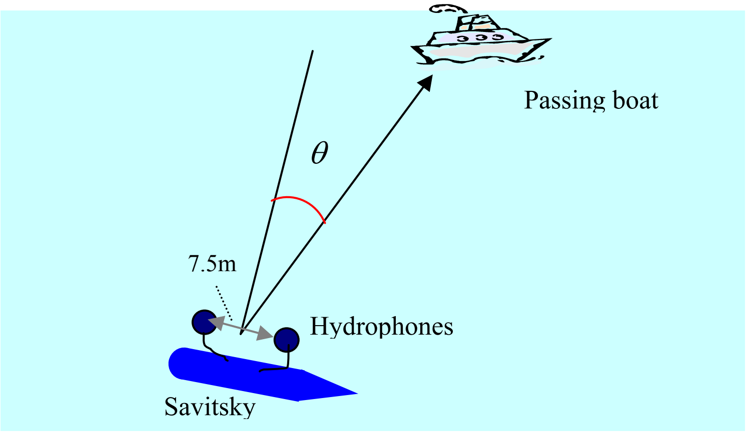

Figure 8. Sketch of the test configuration.

As the ship moves along the river, the angle θ between normal to the hydrophone axis and the direction to the ship changes, which leads to the variation of the time delay between acoustic signals coming to the hydrophones:

$$\tau = \frac{d}{c} \sin \theta \tag{1}$$

where c is sound speed, and d is distance between hydrophones, and where d is small compared to the distance to the ship.

Figure 9 shows spectrogram of the recorded signal and examples of cross-correlation calculated at different time moments. It is clearly seen that time delay between signals is changes from -1.2 ms to 0.8 ms. This means that, according equation (1), the angle θ varied from -13° to +9° in a time interval of 25 s. The distance between the hydrophone array and the passing ship was measured by the video system and the closest distance was 584 m. Hence, an estimation of the ship speed is 9 m/s, or 18 knots.

This example shows the application of a system of two hydrophones for tracking surface traffic bearing. By using several pairs of hydrophones, ship location can be found and tracked over time.

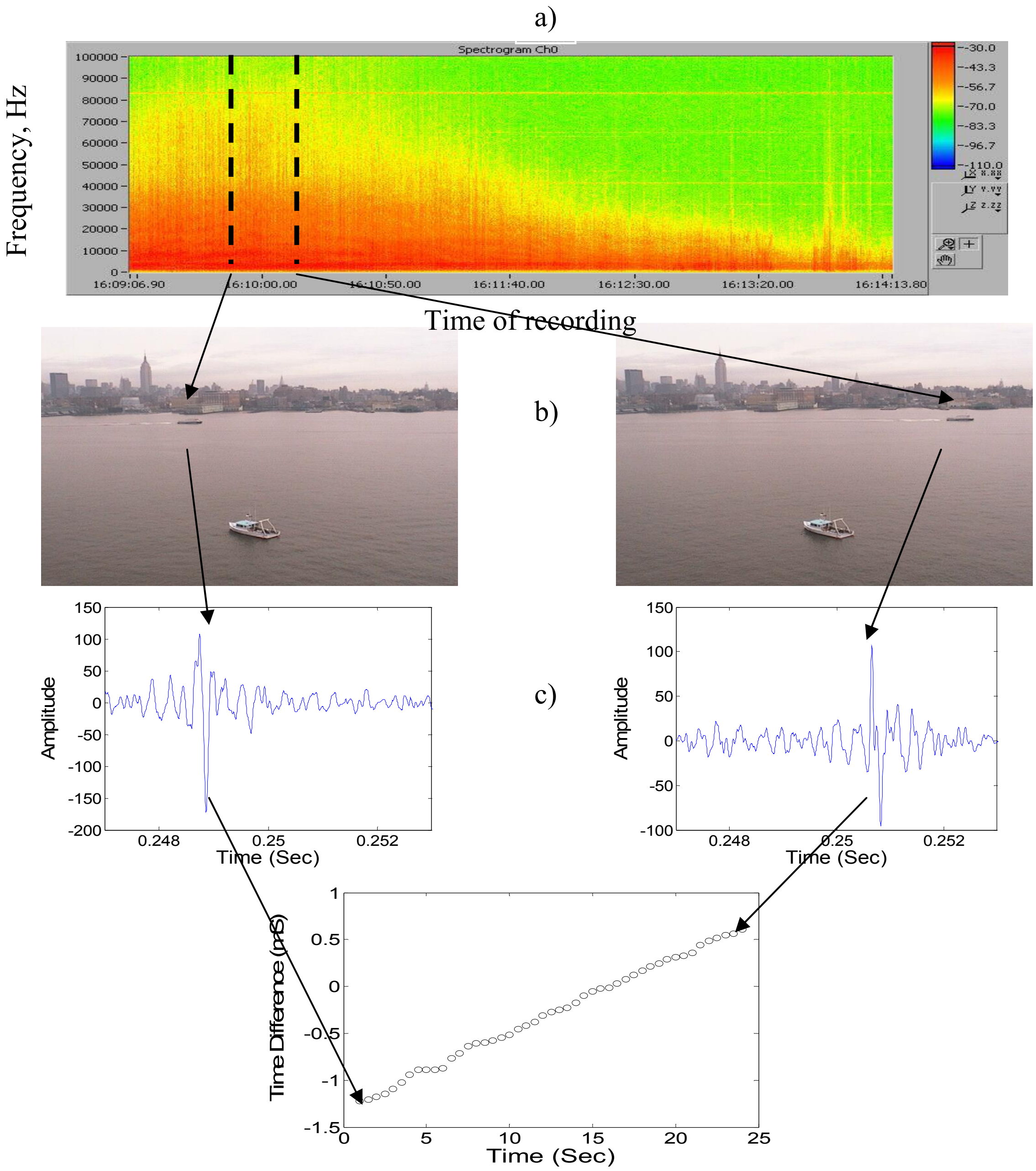

Figure 9. Illustration of cross-correlation method application for finding direction to moving boat from North (left) to South (right). a) Spectrogram of the recorded noise where the time vertical lines show time when cross-correlation was calculated, b) frames from video-surveillance camera at these moments, c) Cross-correlations of the recorded signals for chosen moments and dependence of signal time delay on time showing boat movement.

6. APPLICATION OF JOINT HYDROPHONE AND VIDEO MEASUREMENTS FOR ESTIMATION OF ACOUSTIC ATTENUATION

Underwater acoustic propagation in a shallow water estuary is of interest in acoustic detection of various surface and underwater threats,[1,2,11,12] acoustic tomography,[13,14] and underwater communication.[15,16] The Maritime Security Laboratory (MSL) at Stevens Institute of Technology has recently conducted intensive investigations of acoustic wave propagation in the Hudson River Estuary. One of the important acoustic parameters is the attenuation of sound. The conventional methods of sound attenuation measurements are based on measurements of attenuation between a transmitter and a receiver. These tests require two boats and can not be safely conducted near navigation channels where research vessels could interfere with routine water traffic.

We applied a simpler method of attenuation calculation that is based on measurements of acoustic noise produced by passing ships and simultaneous measurements of ship locations. A similar method was considered in the reference[17] where it was applied in the low frequency range (below 600 Hz). We are interested in a much higher frequency band (10-80 kHz) that can be used for tomography, underwater communication and underwater threat detection is very shallow water.

In our experiments, the level of acoustic noise due to a passing ship was measured by a single hydrophone simultaneously with distance measurements made between the hydrophone and the ship. This distance was measured by a video-based surface traffic tracking system described in the section 4 of the paper.

We present here results of acoustic attenuation measurements conducted on December 21, 2006 in the Hudson River Estuary near Manhattan. The noise levels of passing ships were recorded by a hydrophone (Reson TC4014) placed near the river bottom on a stand of 0.6 m height. The signal from the hydrophone was preamplified, filtered in the frequency band 5-90 kHz, transformed to a digital signal, and stored in a special purpose computer on board the Stevens Research Vessel Savitsky. In signal post-processing, the calculation of the spectral density of the recorded acoustic signal was conducted taking into account the hydrophone sensitivity, preamplifier gain and transfer function of the filters.

Figure 10 shows spectral noise density measured for a fast ferry for ten noise levels for distances between 580 and 724 m with steps of 16m. For estimation of the effective attenuation coefficient we represent the transmission loss (*TL*) as the sum of cylindrical spreading loss plus additional attenuation. The Noise Level (NL) produced by a ship measured at the point of the hydrophone can be written in the form[10]:

$$NL = SL - TL = SL - 10 \log (r) - \alpha r - K \tag{2}$$

where r is the distance between a ship and the hydrophone, SL is the ship source level recalculated to 1 m from the ship, K is parameter characterizing the transition between spherical spreading near a source and cylindrical spreading at great distances. This equation contains three unknown parameters of interest: (SL, K and α). Two of them, (SL,K), characterize the source of sound (i.e. a ship) and the transformation of sound to the channel, respectively. We are most interested in the relative attenuation coefficient, α, as the main acoustic parameter of the channel characterization. For estimation of the attenuation there is no need to know the values of SL and K. The attenuation coefficient was calculated by comparison of the ship noise level NL for distances r and $r + \Delta r$

$$\alpha = \frac{N(r+\Delta r) - N(r) - 10\log(1+\Delta r / r)}{\Delta r} \tag{3}$$

The attenuation coefficients at each frequency were calculated for three vessels using steps between analyzing points, δr, of 16 m. Results of average attenuation coefficient calculations are presented as a function of frequency in Figure 11. It is seen that the attenuation coefficient has weak frequency dependence in the tested frequency range. The averaged value of the attenuation coefficient is 0.058 dB/m with the standard deviation of 0.013 dB/m.

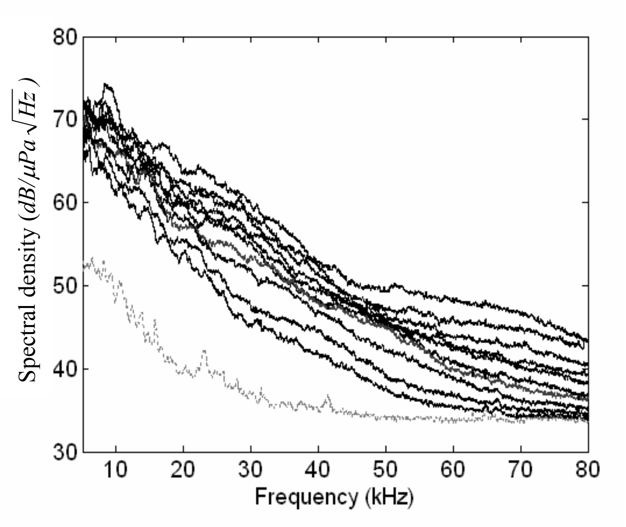

Figure 10. Spectral noise density measured for a fast ferry for ten noise levels for distances between 580 and 724 m with steps of 16m (from the top to bottom, respectively). The lowest level (dotted line) represents recorded ambient noise without any water traffic.

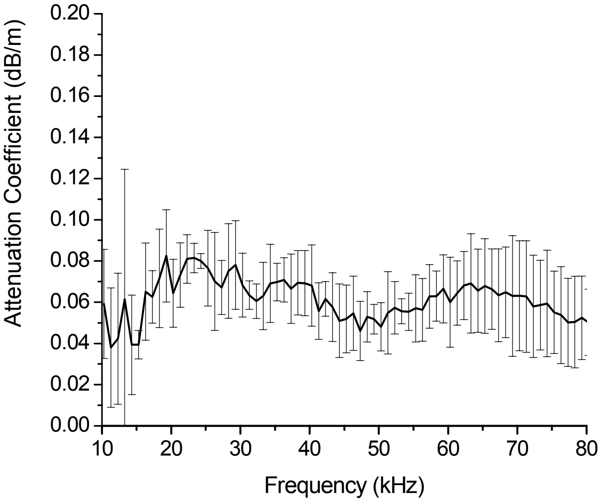

Figure 11. Average effective attenuation coefficient and standard deviation as a function of frequency.

7. NEXT STEPS IN MULTI-MODAL INTRUDER DETECTION

In previous sections, we have described recent acoustic experiments performed as part of Stevens MSL project. In addition, we have described the Stevens video surveillance system for tracking of surface vehicles. These modalities have been combined to determine relative delays in acoustic signals generating as ship signatures as the signals arrive at different hydrophones. This analysis can be extended to determine bearing and location of targets. Also, it has been demonstrated how the combined modalities enable determination of acoustic transmission properties of the estuary. These results can, in turn, be combined with the Stevens NYHOPS system to compare modeled with experimental results of these parameters. Furthermore, it has been observed in our experiments that at some times, an object can be visualized before it is clearly discernible acoustically. At other times, we observe an object acoustically before it has come into the field of view of our cameras. Hence, through data fusion, one system could be made to cue the other, and therefore improve the detection capabilities of the overall system over either individual system by itself. Furthermore, there are some obvious limitations to using visible light video systems due to nighttime situations, fog, and background. This suggests that infrared technology, in some form, be utilized to complement the acoustics and visible light imaging.

These considerations lead us to our target architecture for further experiments, as shown in Figure 12. First, with respect to acoustic measurements, up to this time we have been limited to using hydrophones cabled to a research vessel, as described in Section 2. Going forward, we will augment the MSL architecture with stand-alone acoustic buoys. This will enable acoustic data collection of a larger spatial area, which will reduce triangulation errors, and also allow measurements to be made over extended periods of time without involving a boat crew. In order to reduce transmission bandwidth and storage requirements, remote preprocessing will be done at the buoy. Radio networking will be utilized to transmit the data collected at multiple buoys to a centralized location for further processing and analysis.

The tracking system will be augmented with infrared technology, either mid- or long wave. This will allow the tracker to be used at night or under difficult weather conditions. Even in good weather, however, the infrared modality provides additional information. As seen in the infrared image on the upper right of Figure 6, it is possible to determine areas of different temperatures, such as the location of the boats engine, through the use of infrared technology.

In summary, there are many advantages in maritime safety and security to synergistically combine different modalities of sensing, and to fuse the data so-collected. Experiments to be performed at Stevens in 2008 will further demonstrate these advantages.

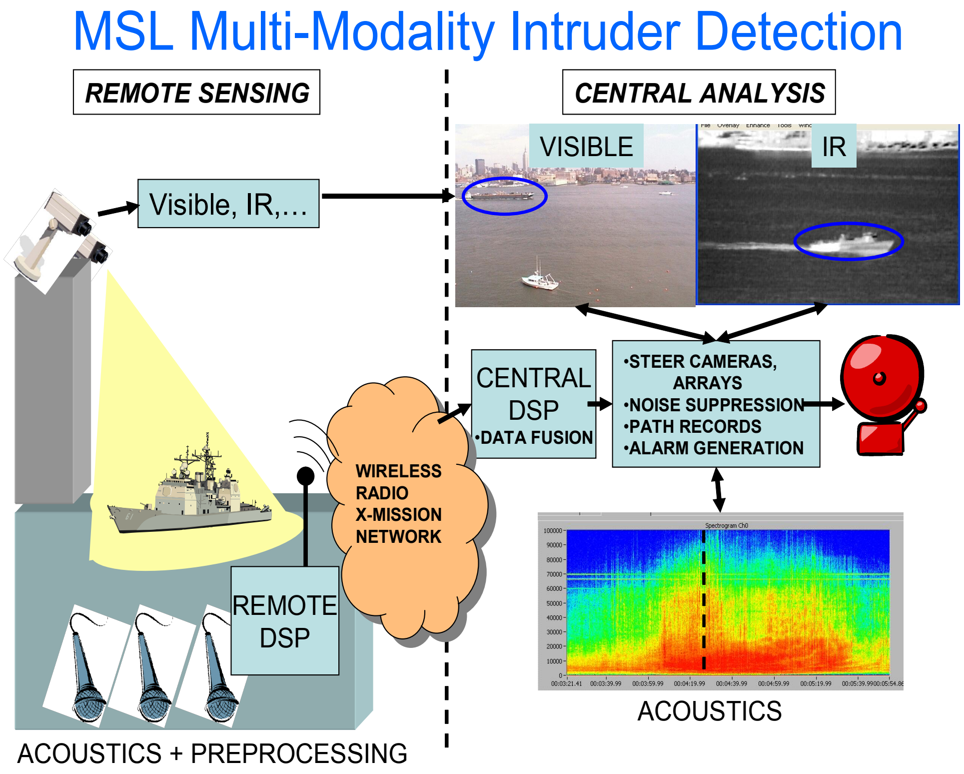

Figure 12. Target architecture for further experiments.

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