Technical Report

OCEAN ACOUSTIC HURRICANE DETECTION AND CLASSIFICATION

Nicholas Makris and Kerry Emanuel

MITSG 03-31

MIT Sea Grant College Program

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Ocean Acoustic Hurricane Detection and Classification

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Objective:

The purpose of this project is to investigate the feasibility of using underwater acoustic sensing techniques to safely and inexpensively estimate the destructive power of a hurricane.

Introduction:

We have experimentally demonstrated that Underwater Acoustic methods may be used to measure the wind speed and destructive power of a hurricane, using data from a NOAA hydrophone in the North Atlantic. From this hydrophone data we determined an empirical relationship $I \sim V^{3.4}$ between a hurricane's wind speed V and the underwater noise intensity I it generates. Given this relationship we show that acoustic intensity measurements can be used to accurately estimate hurricane wind speed. To find this relationship, wind speed data had to be synthesized from satellite and aircraft meteorological measurements. While the results strongly support the use of underwater hydrophone to estimate wind speed, further experiments, with concurrent acoustic and meteorological measurements, are necessary before such an acoustic hurricane wind speed measurement system could be implemented in practice.

This project also includes theoretical modeling of the generation and propagation of hurricane noise through the ocean wave–guide environment. The theoretical modeling shows that underwater hydrophones could be used to accurately measure the wind speeds in a hurricane, and from that measurement classify the destructive power of the hurricane. A single hydrophone, deployed such that a hurricane passes over it, can be used like an anemometer, measuring the hurricane's winds as it moves overhead. Long arrays of hydrophones, in certain deep water ocean environments, can measure the destructive power of a hurricane at ranges of several hundred kilometers.

Hurricanes are one of the most deadly and costly natural disasters. In 1970 a single storm killed more than 300,000 people in Bangladesh (Holland 1993) and in 1900 an unnamed hurricane became the most deadly disaster in United States history killing over 6000 people (Hebert 1993). In 1992 hurricane Andrew became the most costly natural disaster in the United States at an estimated cost of 25 billion dollars (Pielke 1998). Classification of a hurricane's destructive power is critical for hurricane planning. For example, inaccurate classification can lead to poor forecasting and unnecessary evacuations (Emanuel 1999), which are costly, or missed evacuations, which can result in loss of life. These fatalities and cost can be reduced if the public is given timely and accurate advanced warning, but this depends on the ability to accurately classify hurricanes while they are still far from land.

Currently there are two platforms for measuring hurricanes while far from land, satellites and aircraft. While satellites are useful for detecting and tracking hurricanes they are not very accurate in determining the wind speed and wind power needed to classify a hurricane. The most common method for satellite hurricane classification, the Dvorak method, has been known to yield errors in wind speed estimates as high as 40% (Pasch 2000, Franklin 2003, Avila 2001, Stewart 2002). In the North Atlantic this limitation is overcome through the use of reconnaissance aircraft that are capable of making accurate wind speed measurements and hurricane classifications. Unfortunately the expense of these aircraft prevents their use outside the United States (Holland 1993). In this project we consider how underwater acoustic measurements of hurricane wind speed and power may provide an additional technique to augment satellite and aircraft measurements and improve our ability to accurately classify hurricanes.

At frequencies above 10 Hz and wind speeds below 35 kts, it has been shown that the ocean ambient noise field received by a single hydrophone depends significantly on the local surface wind speed (Piggott 1964, Perrone 1970, Farmer 1984, Hodgkiss 1990, Chapman 1993). This relationship has previously been used to estimate the ambient noise based on wind speed measurements (Cato 1997), or conversely, to estimate the wind speed based on ambient noise measurements (Evans 1984, Katz 1984, Nystuen 1997). In this project we consider estimating the wind speeds in a hurricane by measuring the ambient noise it generates.

Experimental Work:

In 1999 NOAA's Pacific Marine Environmental Laboratory (PMEL) deployed several autonomous hydrophones near the Mid–Atlantic Ridge to continuously record the low frequency, 1 to 50 Hz, ambient noise in the ocean (Fox 2001, Smith 2002). While the purpose of this project was to study seismic events, on September 15th of 1999, hurricane Gert (Lawrence 2000) passed directly over one of these hydrophones fortuitously yielding a clear recording of the underwater sound generated by the hurricane. Figure 1 shows the spectrogram of the acoustic field measured by the hydrophone as the hurricane passed overhead. This figure shows high acoustic levels at around 14:00 as the hurricane was overhead

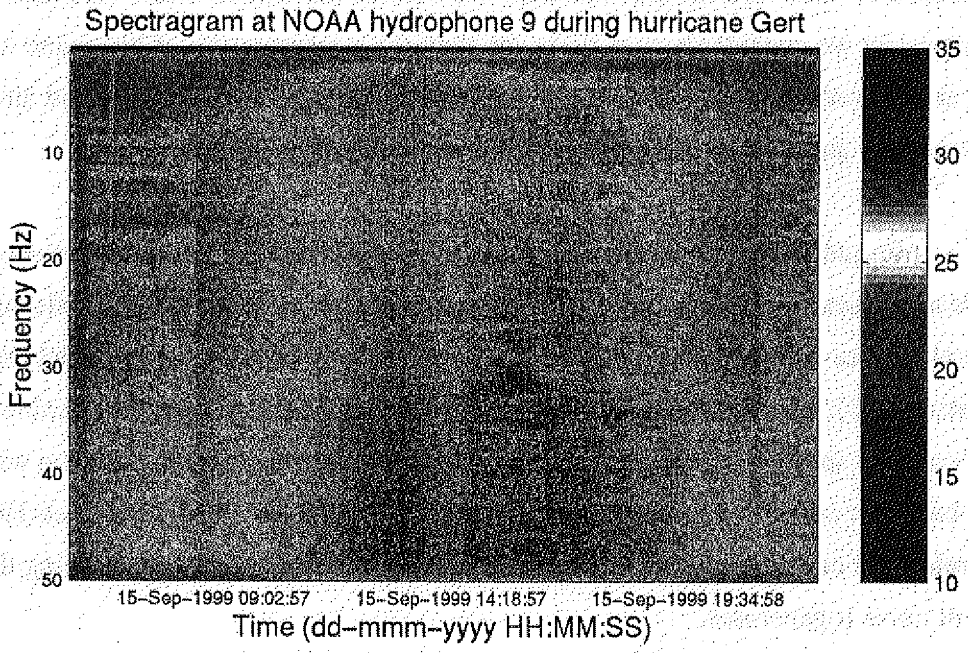

Figure 1: Spectrogram of the acoustic field at the NOAA hydrophone during the time hurricane Gert passed overhead. The high levels at around 14:00 are due to the high winds of the hurricane. We also see a decrease in the acoustic level at 14:18 as the calm eye of the hurricane passed over the sensor.

Figure 1 shows the average power spectral level SL of the noise, between 10 and 50 Hz and averaged over 10 min time windows, during the hurricane's passage. No direct measurements of the wind speed were taken at the hydrophone location so, to correlate spectral level with wind speed, we synthesise the local wind speed record based on available data from US Air Force hurricane hunting aircraft and NOAA hurricane tracking satellites. Figure 1 shows the wind speed profile of the storm from aircraft measurements on Sept 16th, a day after the acoustic measurements(Hurricane Research Division 1999); clearly shown is the characteristic hurricane structure with the powerful winds, up to 47 m/s (92 kt), of the eye wall surrounding the calm center or eye. Satellite location estimates were provided every six hours with an error of +/– 28 km(National Weather Service 1999), effectively yielding an ensemble of possible tracks hurricane Gert could have taken past the hydrophone. The mean satellite estimated track shows that hurricane Gert passed 11 km to the south of the PMEL hydrophone. Each possible track, coupled with the aircraft measured wind speed profile, can be used to synthesise the local hurricane wind speed V at the hydrophone location.

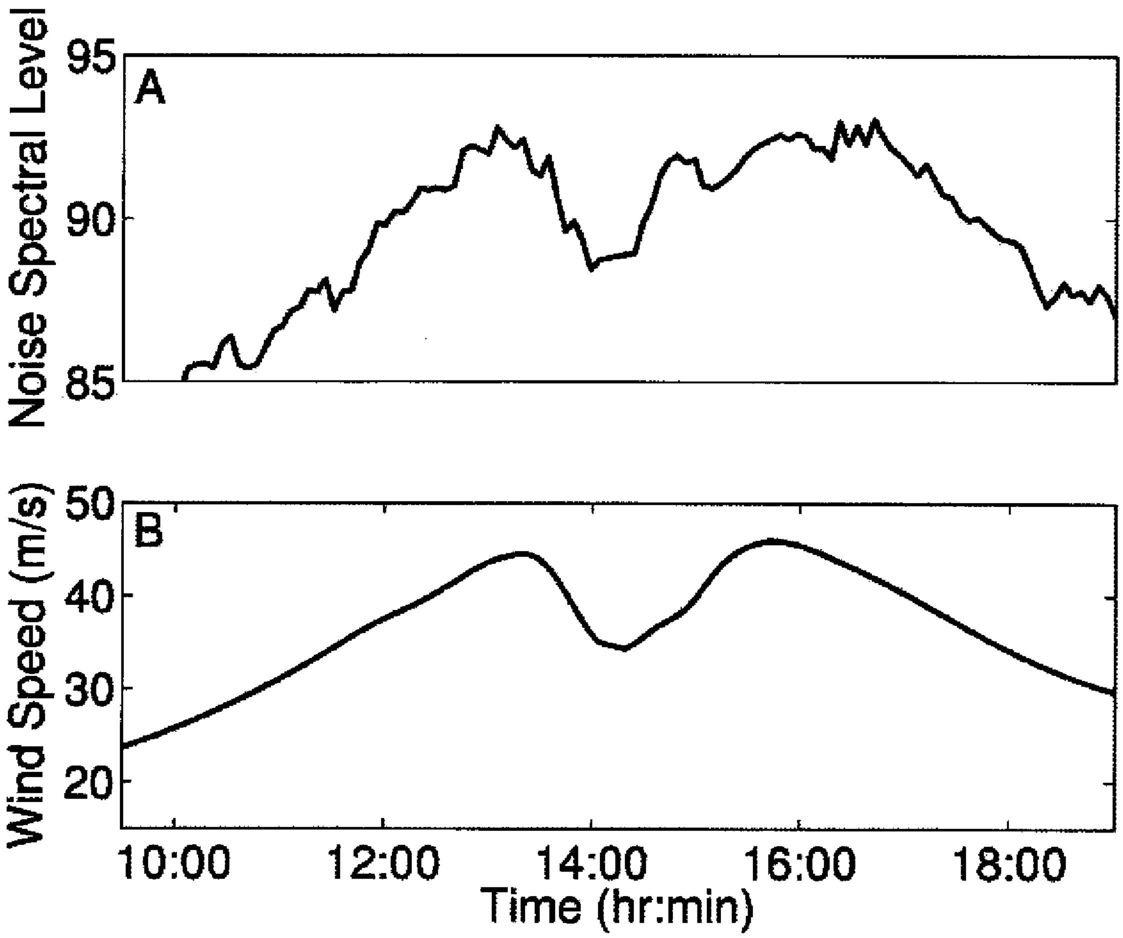

Figure 2: The Average Noise Spectral Level (A) in dB re uPa^2/Hz, from 10 to 50 Hz, received by the PMEL hydrophone on September 15th, and the synthesised wind speed (B) in m/s above the hydrophone based on the likely track. The maxima at 13:30 and 15:30 hours correspond to the powerful hurricane eye–wall and the minimum at 14:30 corresponds to the calm hurricane eye.

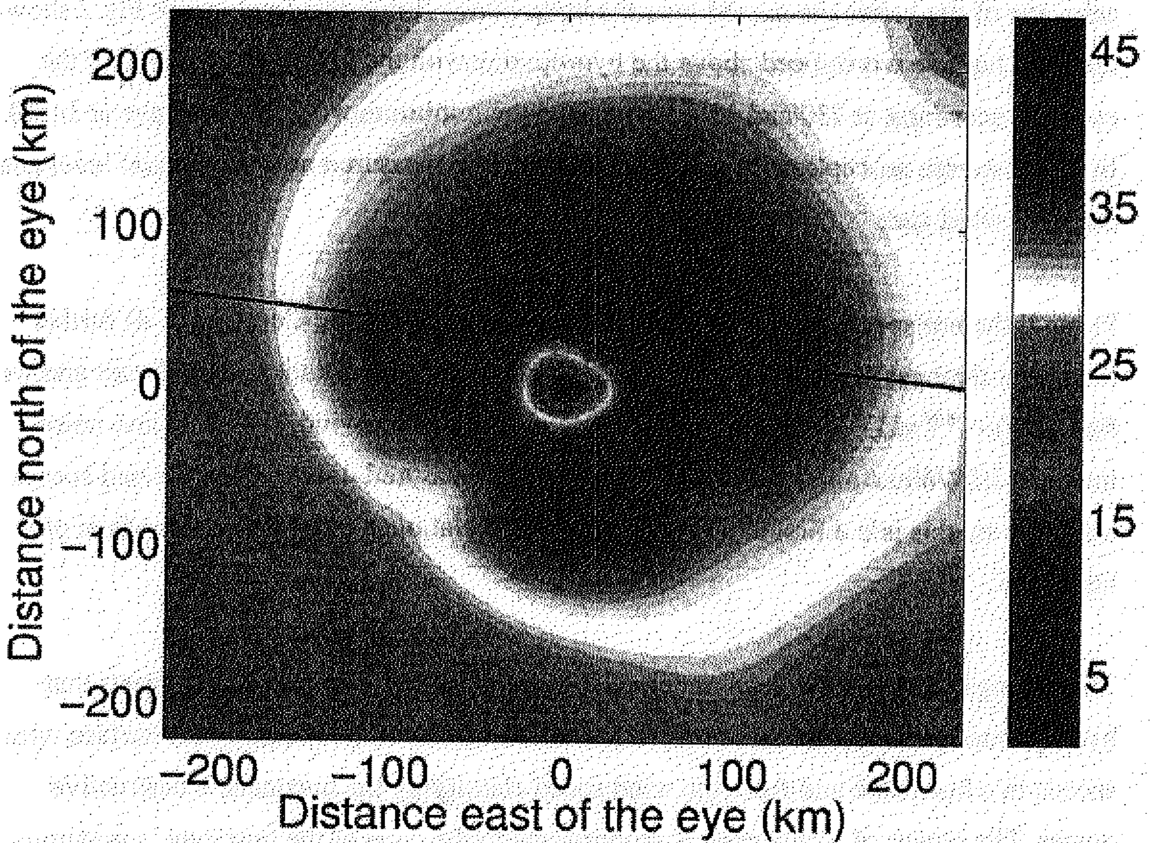

Figure 3: Wind speed profile, in m/s at a height of 10 m, of hurricane Gert from US Air Force reconnaissance aircraft measurements taken on September 16th 1999(Hurricane Research Division 1999). The low wind speed area at the center is the hurricane's eye surrounded by the high winds of the eye–wall. The solid line gives the path of the PMEL hydrophone relative to the hurricane based on the likely track showing that hurricane Gert passed 29 km to the south of the PMEL hydrophone.

For each possible track the power–law hypothesis is tested by calculating the linear regression between the measured spectral level SL and the log of the local wind speed V. The most likely hurricane track is the one where the root–mean–square error (RMSE) of the linear regression between the spectral level and the log of the wind speed is minimised, equalling 0.7. For this likely track, the black line in Fig 3 shows the path of the PMEL hydrophone relative to the hurricane on Sept 15th. In other words hurricane Gert passed 29 km to the south of the PMEL hydrophone; this is within the +/– 28 km margin or error of the satellite estimated track. Note how the powerful eye wall and the calm eye of the hurricane passed over the hydrophone. From this likely track Fig 2 shows the local hurricane wind speed above the hydrophone with the maximum winds of the eye wall occurring at 13:30 and 15:30 hours and the minimum winds of the eye at 14:30. In Fig. 1 we see an exceptional correlation between the measured noise spectral level and the local wind speed.

Plotting the noise spectral level versus wind speed from hurricane Gert (Fig. 4) further illustrates their close correlation. The linear regression of this data is also plotted and we find a $I(f) \sim V^{3.36}$ or $SL=33.6\log(V)+37.1$ relationship between wind speed V and noise intensity I(f). While similar relationships have been measured previously at wind speeds below 15 m/s, this is the first data to suggest such a relationship for the high winds of a hurricane.

This strong relationship between underwater noise and local wind speed suggests that hydrophones could be used as 'underwater anemometers' for estimating the surface wind speeds in a hurricane and from the wind speed classifying the hurricane's destructive power. The power of a hurricane is proportional to the cube of the hurricane's maximum wind speed(Holland 1997) which occurs in the eye wall. So a hydrophone deployed to pass under a hurricane's eye wall could estimate the hurricane's maximum wind speed and total power. Similar underwater acoustic estimates of wind speed have been made previously but at much lower wind speeds(Evans 1984, Katz 1984, Nystuen 1997). As the NOAA/PMEL hydrophone passed under the eye wall of hurricane Gert it recorded a maximum spectral level of 93 dB re uPa^2/Hz which, given our empirical relationship, equates to a maximum wind speed of 46 m/s. This compares favourably to the 47 m/s maximum wind speed measured by reconnaissance aircraft, a difference of only 2%.

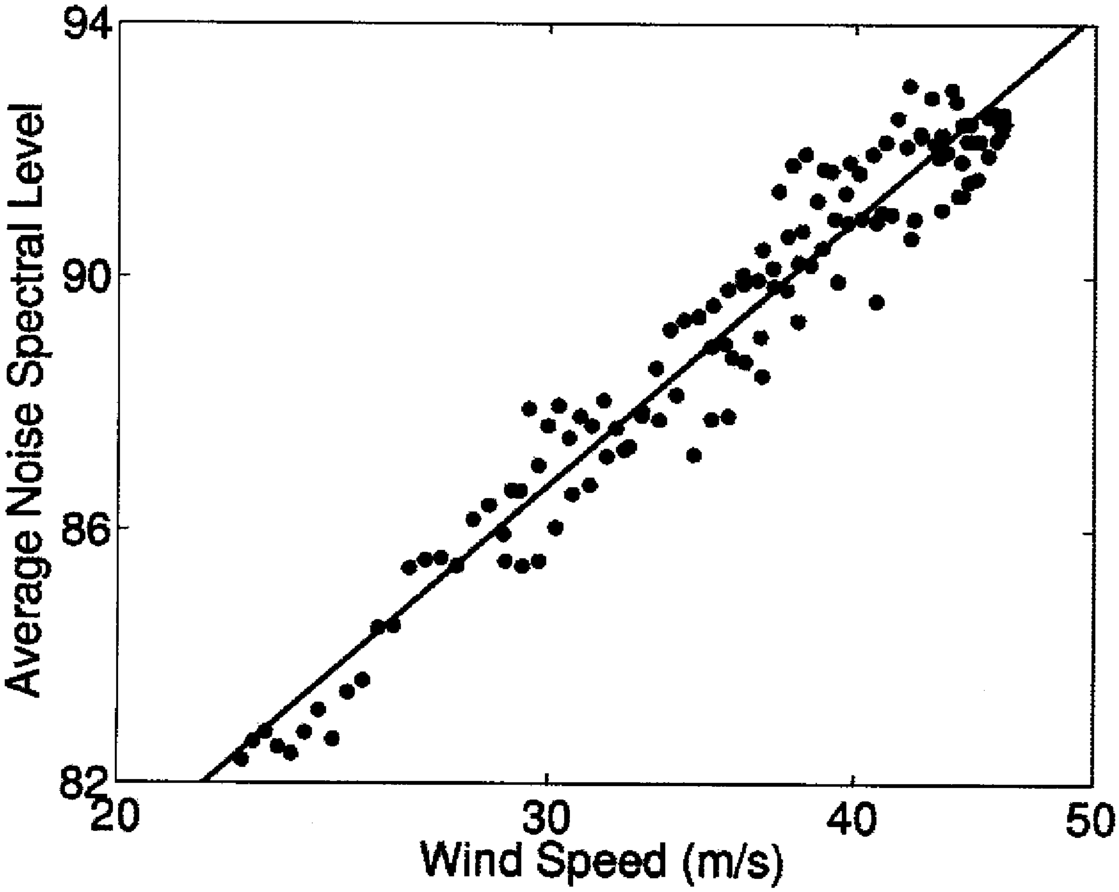

Figure 4: Average Noise Spectral Level SL (dB re uPa^2/Hz) versus surface wind speed V (m/s) on a log scale at the PMEL hydrophone (circles) based on the likely track. The linear regression shows a SL = 33.6log(V)+37.1 relationship between spectral level and log wind speed with a root–mean–square error (RMSE) of only 0.7 dB.

Now we consider the likely accuracy of such a wind speed estimate Figure 3 also shows that there is only a 0.7 dB RMSE between the data and the linear regression. This small RMSE is a result of the large 40 Hz bandwidth and long 10 min time window applied to this data (Makris 1996). This small RMSE illustrates the potential accuracy of using underwater acoustic measurements to estimate wind speed. A 0.7 dB error in spectral level, given the empirical relationship between noise intensity and wind speed, yields a 5% error in wind speed estimate. This is much less than the 40% error common in satellite wind speed estimates(Pasch 2000, Franklin 2003, Avila 2001, Stewart 2002). In fact on Sept 15th and 16th, the Dvorak satellite method estimated Gert's maximum wind speed to be between 59 and 64 m/s(Lawrence 2000) which is 26 to 36% higher than the 47 and 46 m/s estimates made by aircraft and acoustic measurements respectively.

The correlation between underwater noise level and wind speed from hurricane Gert is calculated yielding a 3.36–power relationship between noise intensity and wind speed. Additionally, the high correlation, or small RMSE, suggests that estimates of hurricane wind speed based on underwater noise measurements could be very accurate. A hydrophone could then effectively act as an 'acoustic anemometer', providing an accurate estimate of a hurricane's wind speeds and destructive power. Currently there are many ocean acoustic systems in existence, like the PMEL hydrophones used in this work and the U.S. Navy's SOSUS arrays(Nishimura 1994), that could be used for meteorological measurements and additional systems could be deployed from ships, aircraft, or near shore at relatively low cost.

While this experimental data shows the potential usefulness of underwater sound measurements for estimating hurricane wind speed and power, the exact relationship between wind speed and acoustic intensity requires further experimental verification. Since direct measurements of the hurricane wind speed were unavailable and the wind speed record had to be synthesised from error prone satellite and delayed aircraft data, the empirical relationship between wind speed and acoustic intensity is not conclusive. Further experiments should be conducted with acoustic and meteorological measurements taken simultaneously. Also, future experiments should be conducted to determine the influence of frequency and wave–guide environment on the measurement.

Theoretical Work:

The first part of this project is the theoretical modeling of the acoustic field generated by a hurricane. In our theoretical modeling we will consider using single hydrophones and hydrophone arrays to classify hurricanes through the noise they generate. The field received by these hydrophones is influenced by the wind speeds in the hurricane, the relationship between wind speed and noise generation, the sound speed variation in the ocean wave–guide, the sea surface roughness due to the extreme wave heights in a hurricane, and the frequency dependent attenuation in sea–water. These factors are explored quantitatively to illustrate their effect on our ability to measure hurricane generated sound in the ocean. The expected sound field from a hurricane is then compared to the ambient noise from the lesser surface winds surrounding the hurricane and to shipping noise that becomes significant below roughly 100 Hz. This theoretical analysis gives strong evidence to indicate that underwater hurricane noise can been heard above the typical ocean ambient noise and may be useful in classifying the power of the hurricane. We find that a single sensor placed under a hurricane may accurately measure the local hurricane winds and from this measurement determine the hurricane's destructive power. We also explore linear arrays, typical of what might be deployed by oceanographic or naval vessels, and show how they may be useful in classifying hurricanes at long range.

Figure 5 shows the field that would be received by a single hydrophone in the ocean under a hurricane as a function of depth and range from the hurricane's eye, at 50 Hz, for hurricane rich North Atlantic (A) and Bay of Bengal (B) ocean environments. The wind speed profile of the modeled hurricane is plotted for comparison. From this figure we see that the acoustic intensity under the hurricane closely matches the local hurricane wind speed. So by measuring the acoustic intensity, a hydrophone can be used as an underwater acoustic anemometer. This has the advantage that a hydrophone hundreds of meters underwater would be protected from the intense hurricane winds while a conventional anemometer moored on the sea surface would likely be damaged.

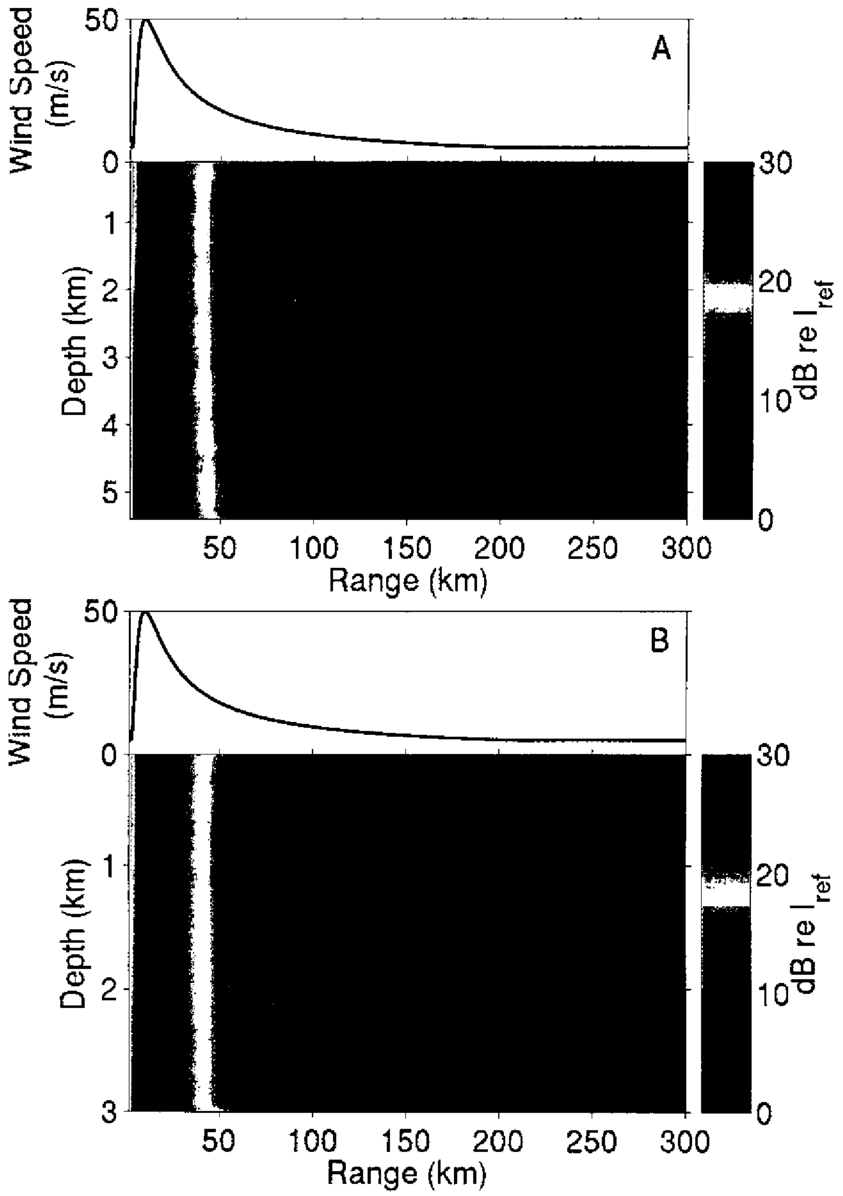

Figure 5: Acoustic intensity in the ocean wave–guide as a function of depth and range from the hurricane's eye in the North Atlantic (A) and the Bay of Bengal (B) at 50 Hz. The wind speed profile of the model hurricane is plotted for comparison. In general the intensity is depth independent and closely follows the wind speed profile. The exception is in the convergence zone structure in the North Atlantic at a depth of 4.7 km and at the surface at a range of 257 km.

We also find that a hydrophone anemometer doesn't measure the wind speed at a single point. Due to the propagation of sound in the ocean wave–guide, a single hydrophone receives sound from a finite area of the ocean surface. This results in a spatially averaged (over about 1 km) estimate of the wind speed. Since the acoustic field is a sum of the ergodic source contributions over this finite surface area, the field received by a single sensor will be Gaussian and long time measurements of this field can yield very accurate results (less than 10% error in wind speed).

Figure 5 also illustrates the difference in the hurricane generated acoustic field between the North Atlantic and the Bay of Bengal. The North Atlantic is deep (5 km) and due to the refraction of sound in the wave–guide the acoustic field generated by the hurricane can propagate to long ranges. So in the Atlantic (Fig.5(A)) we see convergence zones, rays of sound that propagate from the powerful hurricane eye, at a depth of 4.7 km and near the surface at a range of 257 km. We will show later that these convergence zones are useful for measuring hurricanes at long ranges using hydrophone arrays. The Bay of Bengal is much shallower (3 km) and we don't see any convergence zone propagation.

We have shown that a single hydrophone can be used to measure the winds in a hurricane, but only if the hurricane passes overhead. This is because a single sensor primarily measures the wind generated surface noise generated directly overhead. Arrays of hydrophones, however, can be used to spatially filter out the local wind noise sources and measure the field from a hurricane at long ranges. An array can also be used in spatially filtering out contamination from other noise sources like ships or surf. By using long linear arrays of hydrophones, typical of what might be towed from an oceanographic or naval vessel, we find that it may be possible to classify a hurricane at ranges of several hundred kilometers. Figure 6 shows the response of broadside arrays in the North Atlantic at ranges of 257 (A), 289 (B), and 385 km (C) for three different hurricanes. The ranges 257 and 385 km correspond to the fourth and sixth convergence zone distance from the center of the hurricane respectively and 289 km is halfway between the fourth and fifth convergence zones. The largest, class 5, hurricane has a maximum wind speed of 140 knots and the smallest, class 1, hurricane has a maximum wind speed of 64 knots. In Fig. 6 we see that the three hurricanes are distinguishable from each other by roughly five dB. This five dB difference is what we expect since the acoustic power of the hurricane is proportional to roughly the cube of the hurricane's wind speeds, i.e. $100^3 / 64^3 = 5.8$ dB and $140^3/100^3 = 4.4$ dB. Note that only the larger two hurricanes are detectable over the ambient noise in this example.

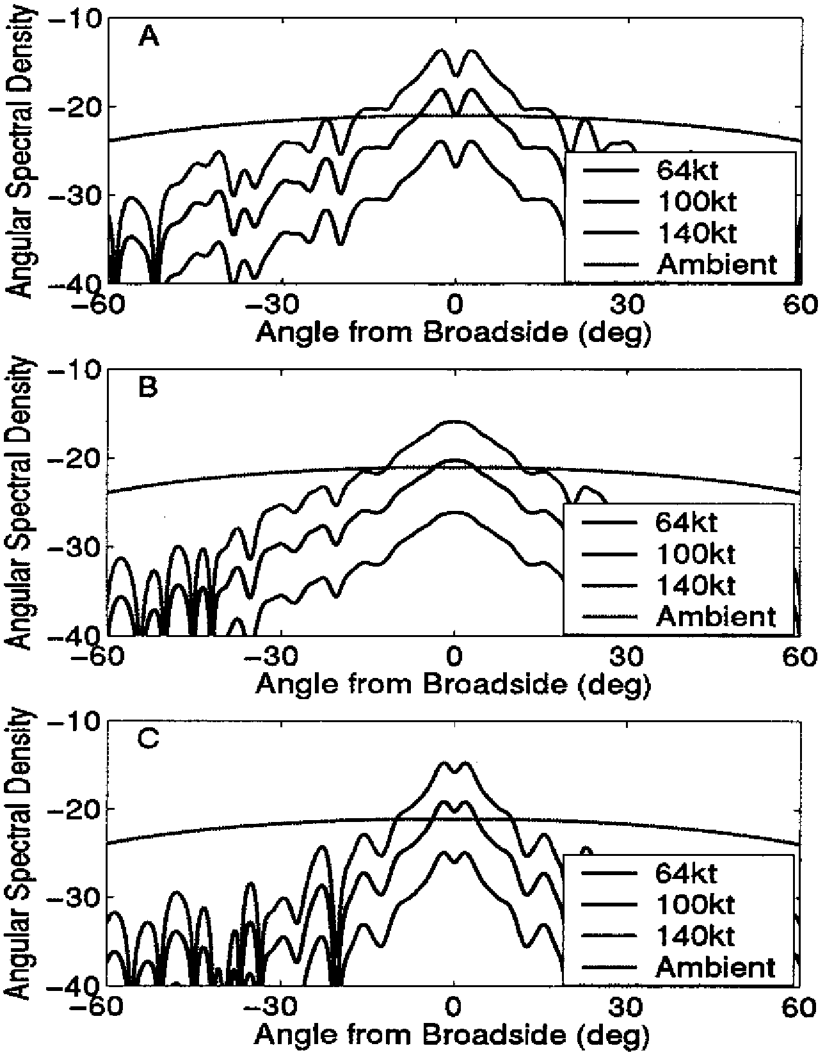

Figure 6: Angular spectral density (in dB) for a 64 element horizontal broadside array as a function of steering angle for hurricane generated noise in the North Atlantic at 100 Hz at ranges of 257 km (A), 289 km (B), and 385 km (C) from the eye of the hurricane. 257

and 385 km correspond to the fourth and sixth convergence zones from the center of the hurricane. 289 km is exactly halfway between the fourth and fifth convergence zones. Curves are shown for a large 140 kt class five, a medium 100 kt class three, and a small 64 kt class one hurricane. The angular spectral density due to ambient noise is plotted for comparison. A steering angle of zero degrees corresponds to the array steered toward the hurricane.

At all three ranges we see an approximately 5 dB change in the angular spectral density between each hurricane which corresponds to the roughly 5 dB change in the hurricane's wind power. For arrays (A) and (C) in a convergence zone the resolution of the array is enough to distinguish the eye (at zero degrees) and the eye wall (at plus of minus three degrees) of the hurricane.

These plots also show the ability of the broadside horizontal array, when placed in a convergence zone (Figs. 6 (A) and (C)), to resolve the important features of the hurricane like the eye and eye wall. At zero degrees we see the eye of the hurricane and at plus and minus three degrees we see the eye wall. This is to be expected since this 64 element array at broadside has an angular resolution of 1.8 degrees which at a range of 257 km corresponds to a spatial resolution of roughly 8 km. This is smaller than the 20 km diameter of this hurricane's eye. The width of the convergence zone can also play a roll in our ability to resolve the eye, however, for this environment and at this range the convergence zone width is roughly 5 km, less than the size of the eye. In reality a hurricane's eye diameter can range from tens of kilometers to over 100 km, but, given the ability of these arrays to resolve a small 20 km eye, they would also be able to easily resolve a much larger hurricane eye.

So we see that a horizontal array can be used to discriminate between hurricanes of different strengths and that the acoustic energy density received by the array is proportional the power of the hurricane. Also an array with sufficiently high resolution located in a convergence zone can resolve the eye structure of a distant hurricane of at least moderate strength. So an array could be used to classify a hurricane at long ranges, however, we do see that the measurement would not be as straightforward as for the single sensor case (Fig. 5).

Conclusions:

From these experiments and models we find that underwater hydrophones represent an enormous, and currently untapped, potential for hurricane research. The strong relationship between wind speed and underwater noise means that a single hydrophone can be used as an 'acoustic anemometer', however, unlike a traditional anemometer, it is underwater and protected from the hurricane winds. Analysis of data from a NOAA hydrophone in the North Atlantic also shows that a single hydrophone can measure the acoustic intensity from a hurricane and from this estimate the hurricane's wind speed and destructive power. Currently there are many ocean acoustic systems already in existence, like the PMEL hydrophones used in this work and the U.S. Navy's SOSUS arrays (Nishimura 1994), that could be used for meteorological measurements; and additional systems can be deployed from ships, aircraft, or near shore at relatively low cost.

These acoustic measurements would not replace satellite methods but would compliment them. A satellites strength lies in its ability to track hurricanes over their life span as they cross entire oceans. The acoustic systems discussed in this paper could not track a hurricane over those ranges but rather could provide an accurate measurement during the time the hurricane is nearby or overhead. These local acoustic measurements could provide a ground truth measurement of the hurricane that would then refine the less accurate satellite estimates.

Further experimental study is required to verify the relationship between the hurricane wind speed and acoustic intensity and to determine the possible influence of environment and frequency.

Appendix A: Students

Joshua Wilson: Ph.D. Candidate, Massachusetts Institute of Technology.

Appendix B: Publicity

"Ear of the Storm,"
Technology Review, 106(6) July/Aug 2003, 5.

"Hurricanes – Listening for Trouble Underwater,"
Marine Scientist, (1) Autumn 2002, 48–49.

Kathy A. Svitil,
"The Sound of the Storm,"
www.discover.com October 1, 2002.

"Sounds Like Trouble,"
The Economist, August 3, 2002, 67.

Bibliography:

L. A. Avila, *Tropical Cyclone Report, Hurricane Iris, 4 – 9 October 2001* (National Hurricane Center, 2001).

N. R. Chapman, and J. W. Cornish,''Wind Dependence of Deep Ocean Ambient Noise at Low Frequencies,'' *J. Acoust. Soc. Am.* **93**(2), 782—789 (1993).

D. H. Cato, and S. Tavener, ''Ambient Sea Noise Dependence on Local, Regional and Geostrophic Wind Speeds: Implications for Forecasting Noise,'' *Appl. Acoust.* **51**(3), 317—338 (1997).

K. A. Emanuel, ''Thermodynamic Control of Hurricane Intensity,'' *Nature* **401**, 665—669 (1999).

D. L. Evans, D. R. Watts, D. Halpern, and S. Bourassa, ''Oceanic Winds Measured From the Seafloor,'' *J. Geophys. Res.* **89**(C3), 3457—3461 (1984).

C.G. Fox, H. Matsumoto, and T–K.A. Lau, "Monitoring Pacific Ocean Seismicity from an autonomous hydrophone array." *J. Geophys. Res.* **106**(B3), 4183–4206 (2001).

D. M. Farmer, and D. D. Lemon, ''The Influence of Bubbles on Ambient Noise in the Ocean at High Wind Speeds,'' *J. Phys. Ocean.* **14**, 1762—1778 (1984).

J. L. Franklin, L. A. Avila, J. L. Bevin II, M. B. Lawrence, R. J. Pasch, and D. R. Stewart, ''Eastern North Pacific Hurricane Season of 2002,'' *Mon. Wea. Rev.* **131**, 2379—2393 (2003).

P. J. Hebert, J. D. Jarrell, and M. Mayfield, *The Deadliest, Costliest, and Most Intense United States Hurricanes of this Century (and Other Frequently Requested Hurricane Facts),* (NOAA Tech. Memo., NWS NHC–31, Washington, DC., 1993).

W. S. Hodgkiss Jr. and F. H. Fisher, ''Vertical Directionality of Ambient Noise at 32N as a Function of Longitude and Wind Speed,'' *IEEE J. Oceanic Eng.* **15**(4), 335—339 (1990).

G. J. Holland (Ed.), *Global Guide to Tropical Cyclone Forecasting*, (World Meteorological Organization, Geneva, 1993).

G. J. Holland, ''The Maximum Potential Intensity of Tropical Cyclones,'' J. Atmos. Sci. 54, 2519—2541 (1997).

E. J. Katz, ''A Note on Indirect Wind Speed Measurements from Ambient Noise,'' *Geophys. Res. Let.* **11**(8), 726—728 (1984).

M.B. Lawrence, *Preliminary Report, Hurricane Gert 11–23 September 1999.* (National Hurricane Center, 2000).

N. C. Makris, ''The Effect of Saturated Transmission Scintillation on Ocean Acoustic Intensity Measurements,'' J. Acoust. Soc. Am. 100(2), 769–783 (1996).

C. E. Nishimura and D. M. Conlon, "IUSS Dual Use: Monitoring Whales and Earthquakes Using SOSUS," *Mar. Tech. Soc. J.*, **27**(4), 13–21, (1994).

NOAA *Hurricane Gert 1330 UTC 16 Sept 1999.* (NOAA/AOML/ Hurricane Research Division, 1999).

NWS, *Hurricane Gert Forecast/Advisory Number 17.* (National Weather Service, Miami, 1999).

J. A. Nystuen, and H. D. Selsor, ''Weather Classification Using Passive Acoustic Drifters,'' *J. Atm. Ocean. Tech.* **14**, 656—666 (1997).

R. J. Pasch, *Tropical Cyclone Report, Hurricane Debby, 19 – 24 August 2000}* (National

Hurricane Center, 2000).

A. J. Perrone, ''Ambient–Noise–Spectrum Levels as a Function of Water Depth,'' *J. Acoust. Soc. Am.* **48**(1), 362––368 (1970).

R. A. Pielke Jr., and C. W. Landsea, ''Normalized Hurricane Damages in the United States: 1925–1995,'' *Wea. and Forecasting* **13**, 621–631 (1998).

C. L. Piggott, ''Ambient Sea Noise at Low frequencies in Shallow Water of the Scotian Shelf,'' *J. Acoust. Soc. Am.* **36**(11), 2152––2163 (1964).

D.K. Smith, et al, "Hydroacoustic monitoring of seismicity at the slow–spreading Mid–Atlantic Ridge." *Geophys Res Lett.* **29**(11), 13–1–13–4 (2002).

S. R. Stewart, *Tropical Cyclone Report, Hurricane Kyle, 20 September – 12 October 2002* (National Hurricane Center, 2002).