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Relating Ocean Acoustic Ambient to Ocean Surface Dynamics

A Paper Presented at the 121st Meeting of the Acoustical Society of America at Baltimore, MD, 29 April 1991

R.M. Kennedy
Test and Evaluation Department
West Palm Beach, Florida

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PREFACE

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13. ABSTRACT

The acoustical significance of ocean surface dynamics is well known. Motivation for establishing the causal relations between these two physical processes has both underwater acoustic system noise reduction and oceanographic remote sensing objectives. The goal has eluded investigators because of the complexity of both the acoustic and oceanographic mechanisms involved. Significant contributions have been made by a progression of laboratory measurements of various spatial scales as recently reported [H. Medwin, J. Acoustic. Soc. Am. 88, sup 1 (1990) and L.A. Crum et al., J. Acoustic. Soc. Am. 88, sup 1 (1990)]. The work discussed here continues the progression in spatial scales by utilizing a relatively deep water basin (The Tongue of the Ocean, the Bahamas) in a quasi-controlled environment which made a broadband measurement (40 to 4000 Hz) of the vertical directional spectrum of the ambient acoustic field. The 1-year data base of directional spectrum are dominated by local (fetch limited) water surface conditions over a wide range of environmental conditions. While the exploratory nature of the experiment limited the amount of supporting meteorological and oceanographic measurements made, the results give additional credence to the role of entrapped air bubbles and bubble clouds in the generation of acoustic ambient. Sea surface-generated acoustics is shown to be dependent on a fundamental nondimensional variable describing the air-sea boundary process and the rate of energy dissipation caused by wave-breaking in the gravity wave equilibrium range.

This document is a transcript of the presentation given by Dr. Kennedy on April 29, 1991, at the 121st Meeting of the Acoustical Society of America at Baltimore, MD.

SLIDE 1:

For decades experiments have found a clear correlation between underwater acoustic ambient and the local wind speed. The literature has numerous examples of log-log plots of acoustic spectral level and wind speed. It has been equally clear for some time that over a significant frequency range of interest that the wind is not directly causing the acoustic radiation that is measured. It is now a familiar idea that sea surface-generated acoustic radiation is related to wind speed through the wave-breaking process which is the source of bubbles (Medwin and Beaky, 1989[1]) and spray (Guo, 1987[2]) responsible for the sound generation. It is the objective of this presentation to relate measured sea surface-generated dipole sound source levels to environmental variables which characterize the air-sea boundary processes. The approach taken was to use measurements obtained in a water basin in which both the acoustic and oceanographic conditions are locally generated and relatively simple (Kennedy and Goodnow, 1990[3]). This quasi-controlled environment can be viewed as a succession to the laboratory measurements of Medwin, 1990[4], and Crum, 1990[5] which have so significantly contributed to this subject. I believe that the outcome of the present study reinforces their results relative to the importance of air entrainment in the generation of acoustic radiation.

OBJECTIVE

Relate measured sea surface-generated dipole sound source levels to environmental variables which characterize air-sea boundary processes.

APPROACH

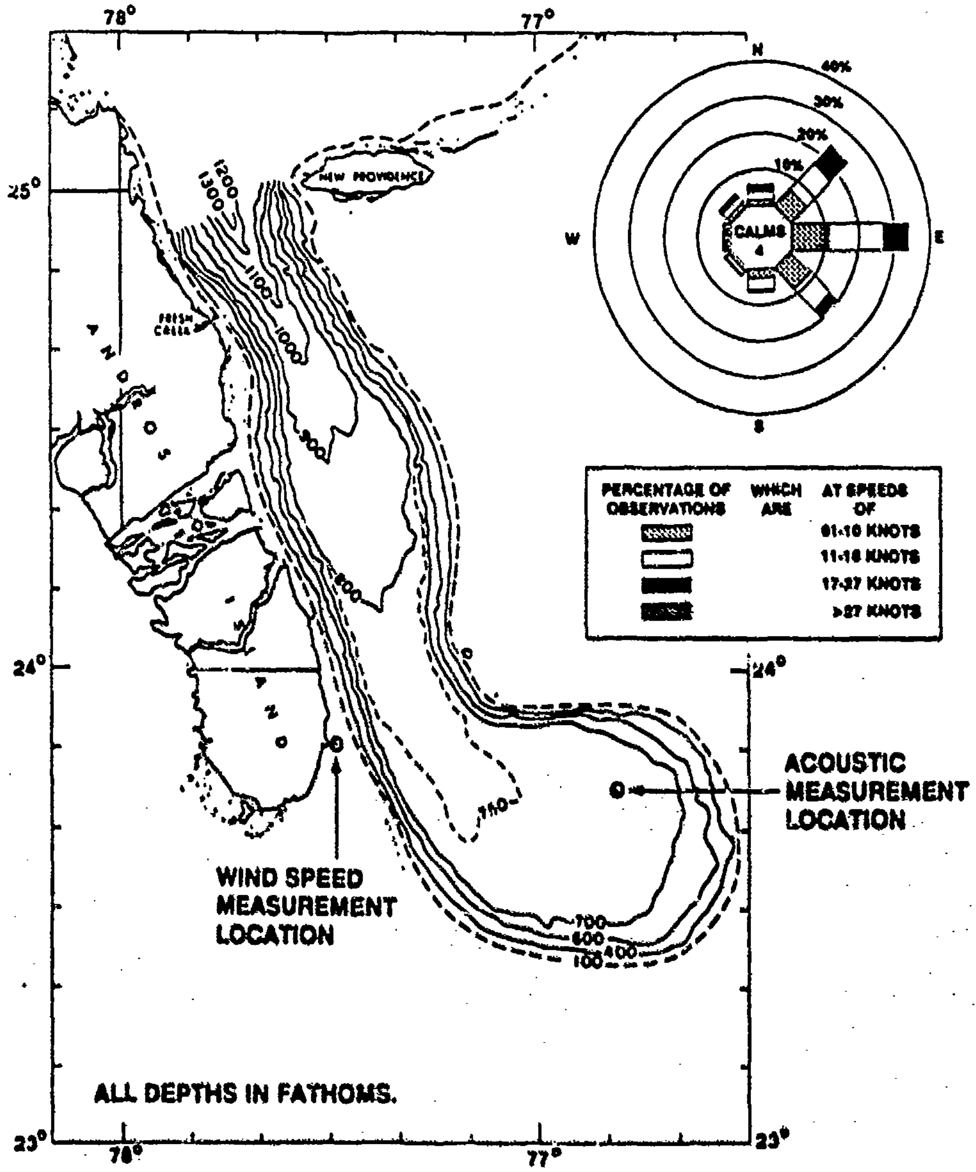
Utilize measurements from a water basin in which both the acoustic and oceanographic conditions are locally generated and relatively simple.

SLIDE 2:

The subject measurements were made in a northeastern section of the cul-de-sac of the Tongue of the Ocean in the Bahamas. It is relatively deep water basin, totally isolated from global and even local shipping. The location is also oceanographically isolated from distant sources. As a consequence, the resulting acoustical and oceanographic conditions are almost totally caused by the local wind. This slide contains an annual summary of the wind speed and direction. The wind fetch in the direction of the typical wind is essentially unlimited while the fetch for wave growth is approximately 10 nmi. The near-surface ocean dynamics are determined only by the local wind and tide.

The data base consists of 101 trials taking place over a ten-month period. The minimum time between trials is 48 hours which, for the most part, assured statistical independence.

MEASUREMENT LOCATIONS



SLIDE 3:

The trials consisted of measuring the spatial (vertical) cross-spectral density function and the local wind speed at a 10-meter elevation. From these measurements the acoustic source level (per unit area of the sea surface) of a dipole source element was calculated. The calculation procedure back-propagated the measured values to the sea surface and then isolated the dipole component via a parametric spectral estimation process. The dipole source level estimation procedure differed from previous approaches in the following ways:

- The presence of a dipole component was never assumed, but rather always tested for by matching to the total spatial spectrum measured.

- If and when multiple acoustic components were present, the dipole source level was associated only with the dipole component.

- Other sources such as modal responses of the basin are identified and removed.

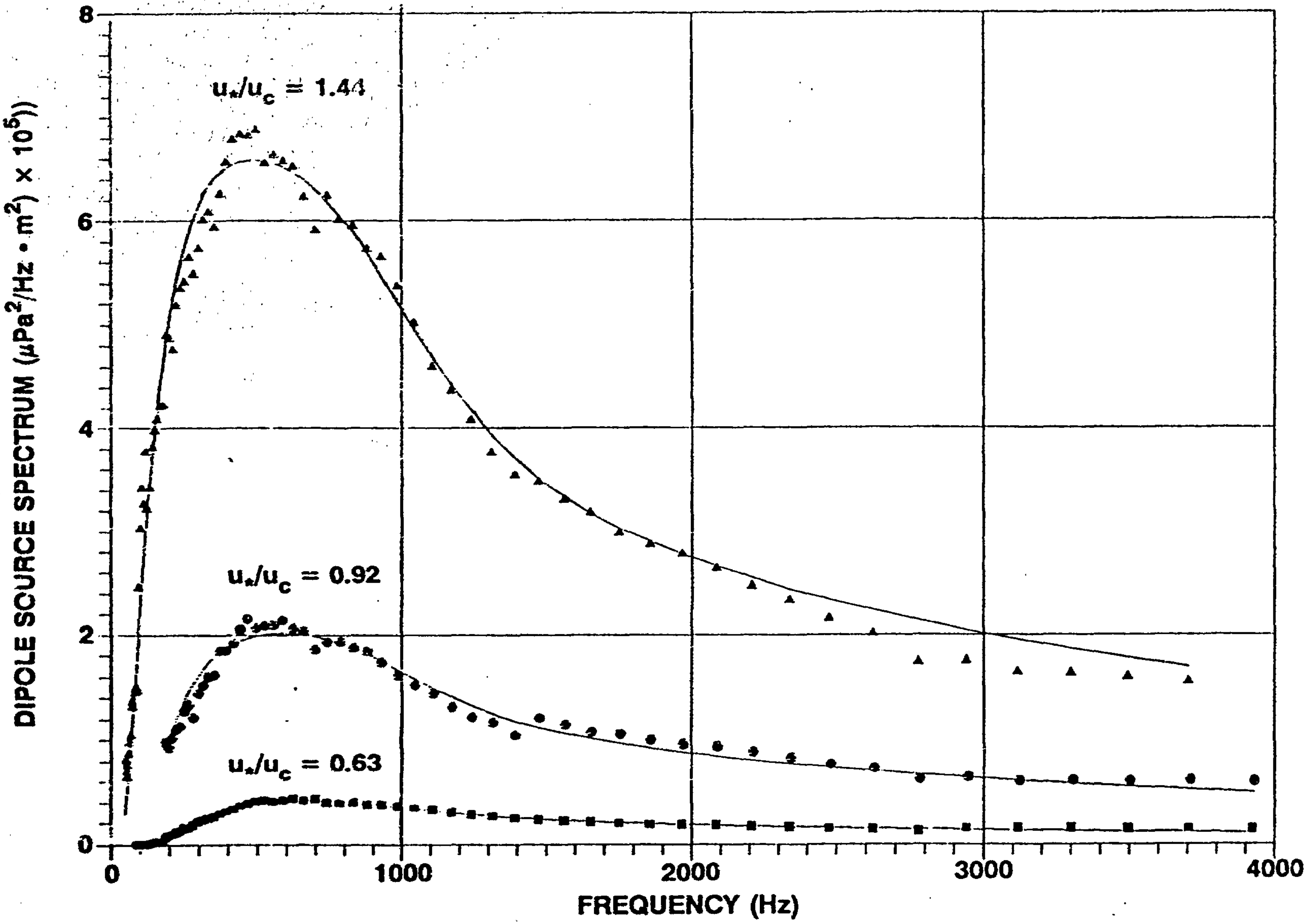
DATA PROCESSING SUMMARY

- Measure Vertical Cross-Spectral Density
- Calculate Sea Surface Sound Dipole Source Area Density ($\mu Pa^2/Hz \cdot m^2$ @ 1m)
  - Each Trial Tested for Dipole Presence by Pattern Matching
  - Dipole Source Strength Chosen to Match only Dipole Pattern
  - "Other" Source Patterns Identified and Removed

SLIDE 4:

This linear axis figure illustrates the general character of the dipole source frequency spectrum. The abscissa is frequency and the ordinate is spectrum level. These are three examples of the 101 spectra measured. The spectrum are clearly bandpass with a decaying high frequency end and an abrupt low frequency cutoff. The wind speed is parametized by the nondimensional wind surface friction velocity used by Kerman, 1984[6]; i.e., the wind friction velocity is nondimensioned by the minimum phase speed of the capillary-gravity wave field. The friction velocity is calculated assuming a logarithmic wind profile under neutrally stable conditions (Wu, 1980[7]). Unity value of this variable represents the onset of clearly visible spilling whitecaps. Note that the basic character of the spectrum is unchanged in shape independent of whether whitecaps are or are not present. This point will be returned to later in the presentation.

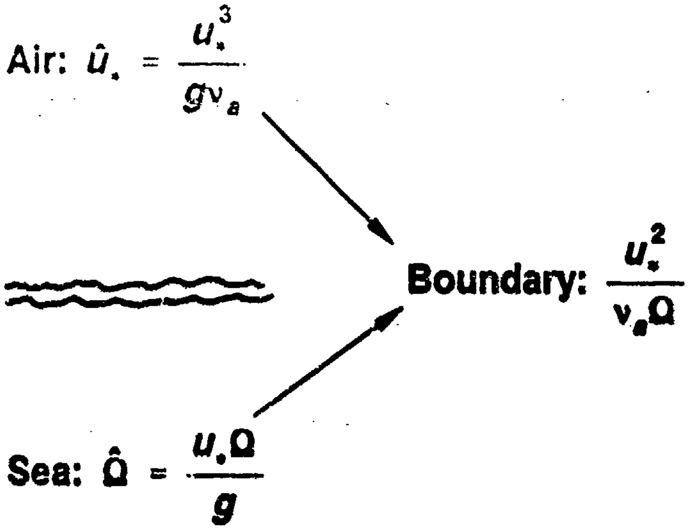
EXAMPLES OF DIPOLE SOUND SOURCE SPECTRUM



SLIDE 5:

To test the hypothesis that the dipole source levels are associated with wave-breaking we seek a variable associated with the air-sea boundary process. Clearly wind speed alone is not that variable. Toba, 1986[8], argued that there are only two nondimensional variables determining the local physical processes. The wind is best characterized by it's friction velocity which is here nondimensioned by the kinematic viscosity of air and the gravitational constant. The state of the sea is expressed by the frequency of the dominant wind-wave component. This frequency is nondimensioned by the wind friction velocity which caused the gravity wave and again the gravitational constant. Since g is a common constant for both variables it can be eliminated to form the boundary variable shown. This variable has been widely used to describe the overall conditions of the air-sea boundary processes. Beyond a critical value of 10^3 the percentage of waves passing a fixed point that are breaking, the percentage of whitecape coverage, the dimensionless roughness length associated with the air flow over water, and certain aerosol salt concentration variables have all been shown to be proportional to this variable. One intuitively sees that the variable implicitly introduces fetch into the description that is so obviously lacking in a wind speed, or wind friction velocity, explanation.

WAVE-BREAKING NONDIMENSIONAL VARIABLE
(Toba and Koga, 1986)



Air: $\hat{u}_* = \frac{u_*^3}{g\nu_a}$

Boundary: $\frac{u_*^2}{\nu_a\Omega}$

Sea: $\hat{\Omega} = \frac{u_*\Omega}{g}$

u_*: Wind-friction velocity

Ω: Frequency of dominant gravity wave component

ν_a: Kinematic viscosity of air

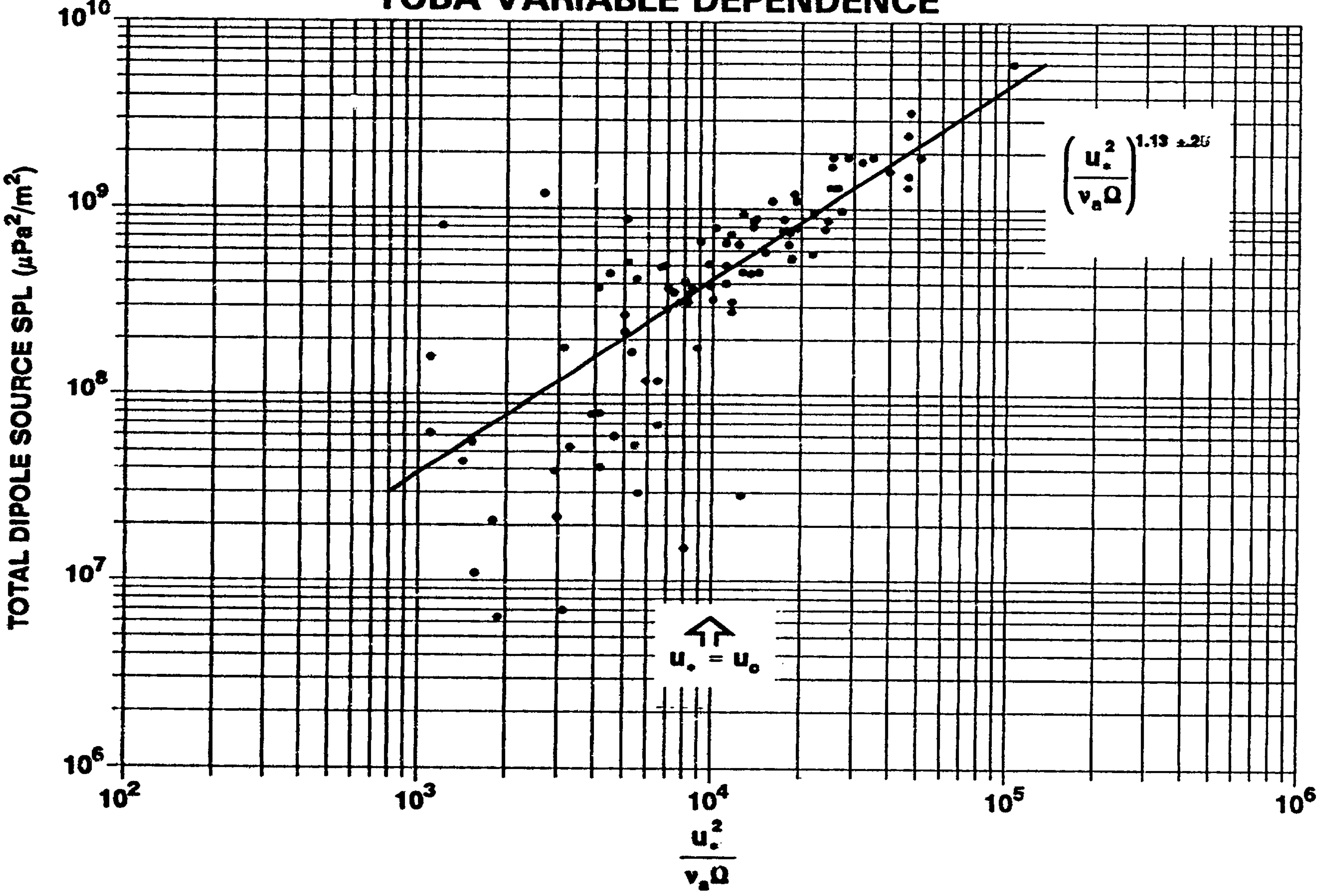
g: Gravitation constant

SLIDE 6:

In this slide the total dipole source level is presented as a function of the Toba variable. The ordinate is the frequency integrated dipole source strength in $\mu Pa^2/m^2$. The abscissa is the dimensionless Toba variable. There were no provisions made in the experiment to measure Ω and thus, it was calculated from the measured wind speed and direction combined with the measurement geometry using a JONSWAP model (Hasselmann, et al, 1973[9]). There are two characteristics to be noted in this figure. First, the dipole sound production is seen to be directly proportional, within measurement error, to the Toba variable describing the air-sea boundary dynamics. Second, the variability of the experimental points partitions the data into two distinct regions separated by the point at which the friction velocity is equal to minimum phase speed of the wind-wave field. The change in character of the data above and below unity value of the nondimensional friction velocity has been commented on previously by Kerman, 1984[6]. Kerman showed that this marks the point where the turbulence at a free surface is sufficiently energetic to exceed the energy associated with the surface tension. Wu, 1980[7] also identifies this epoch as the minimum wind-friction velocity for which airflow separation occurs on the lee side of gravity waves. Amorocho and DeVries, 1980[10] show that in open water data, this point begins a transition range in friction velocity and the 10-meter "wind stress coefficient". It is at this value of friction velocity that the ocean surface changes from aerodynamically smooth to rough and that the surface turbulent eddies are energetic enough to regularly entrap air bubbles.

Despite the change in character of the sound pressure level relative to the independent variables, the spectral shape, as seen in the previous slide, remains the same indicating the possibility that entrained air bubbles remains the acoustic source. Monohan and Lu, 1990[11] note that the advent of bubble injection into the water column from the surface occurs approximately at a value of the Toba variable of 10^3. Above 10^4 turbulent air entrainment is probably the principal source of air bubbles. Below 10^4 turbulent-induced bubble trapping is at least partially suppressed by surface tension and finite amplitude capillary waves may be the source of bubble trapping. However, Updegraff, 1989[12], visually identifies "small wavelet spills" during light winds indicating that turbulent entrainment is not totally suppressed.

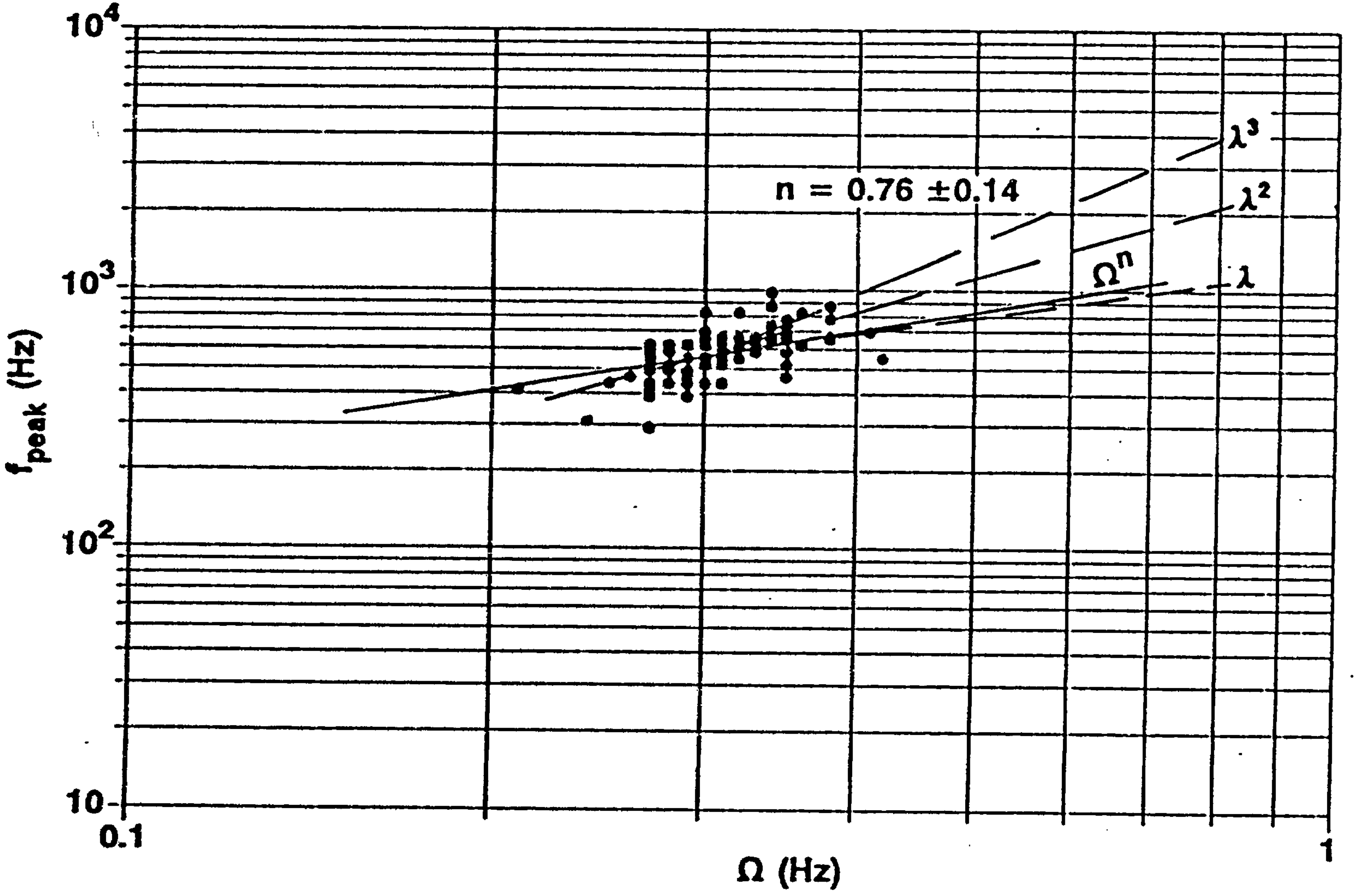
TOBA VARIABLE DEPENDENCE



SLIDE 7:

Prosperetti, 1988[13] and Carey and Browning, 1988[14] have hypothesized that clouds of bubbles which oscillate collectively at sub-kilohertz frequencies are important contributors to the acoustic ambient. If this is true, then the frequency at which the dipole energy is maximum should be related to bubble cloud size which in turn might be related to the dominant wavelength of the gravity wave spectrum; i.e., lower frequency seas would generate lower frequency acoustic radiation. To test this reasoning this figure illustrates the frequency of peak acoustic energy (on the ordinate) plotted versus the frequency of the dominant gravity wave component. The two variables are seen to be proportional. Yoon and Crum, 1991[15] have recently shown, that for a homogeneously populated bubble cloud with a fixed void fraction, that the resonant frequency is inversely proportional to the cloud volume. If this relation is approximately true at sea, then the bubble cloud volume should be proportional to some power of the wavelength of the gravity wave field. The slopes for these powers are shown on the figure. Comparison with the regression line indicates the bubble volume is proportional to the wavelength of the dominant gravity wave component.

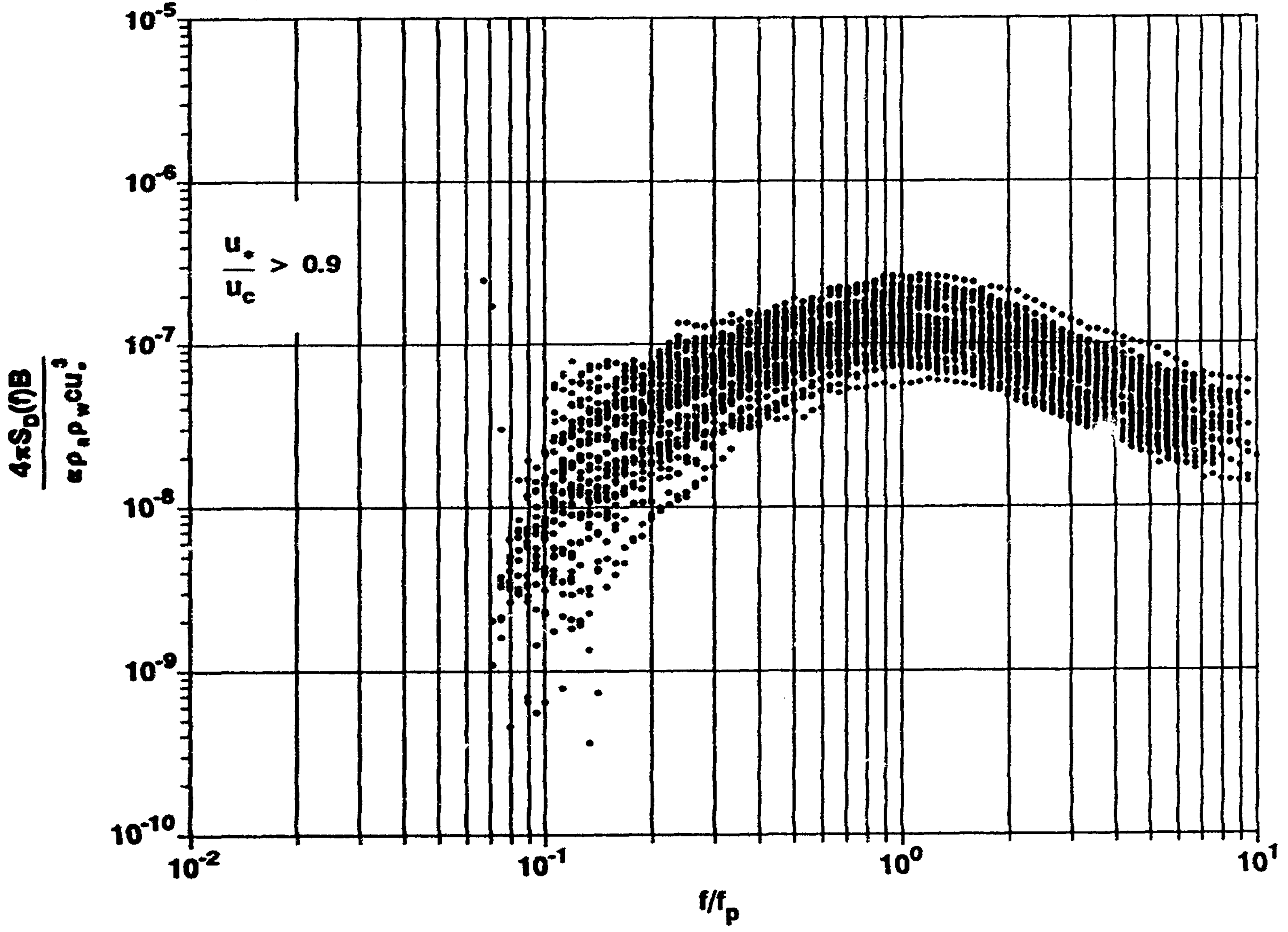
GRAVITY-WAVE COMPONENT DEPENDENCE



SLIDE 8:

If it is asserted that the acoustic radiation caused by the sea surface is due to wave-breaking, then it is reasonable to compare the rate of energy being dissipated at the surface by wave-breaking with the rate of acoustic energy being radiated. Phillips, 1986[16], 1988[17] derives an expression for the total rate of energy input into the surface-layer turbulence by wave-breaking in the gravity wave equilibrium range. The ordinate of this figure is the dipole acoustic energy rate per unit surface area nondimensioned by the Phillips expression for the rate of energy dissipated per unit surface area by wave-breaking in the gravity wave equilibrium range. The abscissa is the acoustic frequency nondimensioned by the frequency of peak acoustic energy as did Kerman, 1984[6]. Note that only trials having a nondimensional friction velocity greater than 0.9 are included. The figure demonstrates a coalescing of the spectrum within a factor of four. Note that an nondimensional frequencies less than 0.25 that the data indicates larger scatter. At these lowest frequencies it is reasonable to expect the acoustic radiation to be influenced by the dominant gravity wave component, not just the equilibrium range. This is consistent with the previous discussion.

EQUILIBRIUM RANGE GRAVITY-WAVE SCALING



SLIDE 9:

This slide summarizes the environmental variables that the data analysis has indicated are fundamental to establishing the causal relation between sea surface dynamics and sea surface-generated acoustic radiation. The present work indicates that sound production depends on a dimensionless variable which involves the wind friction velocity, the air kinematic viscosity, and the frequency of the dominant component of the gravity wave field. These same parameters, along with sea water density, are the basis of a nondimensionalization which produces a universal function relating acoustic power generated to the rate of energy dissipated by wave-breaking in the gravity wave equilibrium range. Furthermore, the acoustic spectral peak appears to be proportional to the wavelength of the dominant component of the gravity wave field.

The analysis presented indicates that the acoustic generation is spectrally similar over all wind speeds but that the relation of the acoustic energy generated to the air-sea boundary description is distinctly different depending on whether the surface is aerodynamically smooth or rough. During smooth conditions there appears to be an environmental dependence not found in this experiment. Additional environmental measurements that would have been useful are whitecap coverage, surface currents, and surface tension.

SUMMARY OF PRINCIPAL ENVIRONMENTAL VARIABLES

For $u_* \gtrsim u_c$

- Wind-friction velocity
- Gravity-wave directional spectrum
- Air kinematic viscosity and density

For $u_* < u_c$

- Wind-friction velocity
- Gravity-wave directional spectrum
- Air kinematic viscosity and density
- Whitecap coverage
- Surface currents
- Surface tension

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