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Measuring the Vertical Directional Spectra Caused by Sea Surface Sound

A Paper Presented at the 119th Meeting of the Acoustical Society of America, State College, Pennsylvania, 24 May 1990

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PREFACE

This report was prepared under Project S64838 and 638V11, Principal Investigator R.M. Kennedy (Code 3802). The work reported herein was performed as part of the Naval Underwater Systems Center program of Independent Research and Independent Exploratory Development (IR/IED), Program Manager Dr. K.M. Lima, and the Test and Evaluation Department Acoustic Range Initiative, Program Manager J.H. Keegan.

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J.H. Keegan, Code 38
Head, Test and Evaluation Department

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19. ABSTRACT

The objective of the measurements discussed here is the development of a database of directional spectra obtained in an acoustically isolated area (Tongue of the Ocean, The Bahamas) where the acoustic ambient is principally controlled by the local (observable) sea surface conditions. The purpose of the database is the identification of a model of the space-time statistics of sea surface sound. A wideband (40 to 4000 Hz) vertical acoustic linear antenna system was used. Data logging took place in a remote, autonomously operating subsurface buoy system. Recording restrictions limited each of the seven octavely nested apertures of the sensor system to four wavelengths. However, quite adequate spatial resolutions of the directional spectral estimates were obtained using a physically based parametric model of the random process. The results of the initial two-month deployment (wind speed range of 2 to 16 m/s) are discussed here. The measured directional spectra are displayed as a function of frequency, elevation angle, and surface friction velocity. The sea surface sound source structure is discussed.

This document is a transcript of the presentation given by Dr. Kennedy on May 24, 1990, at the 119th Meeting of the Acoustical Society of America, which was sponsored by Pennsylvania State University, in State College, PA.

SLIDE 1: (1.5 minutes)

Both the design and the analysis of underwater acoustic systems are dependent on good models of the local acoustic ambient. It is well known that the sea surface generates acoustic radiation that often dominates the system output noise field, and despite considerable effort, improvements in the models remain necessary when hydrophone arrays having vertical apertures are used in a wide range of environments. The objective of the task that I am discussing is the development of a model of the vertical directional spectrum due to that sea-surface-generated radiation. Directional spectra has been chosen because it is a readily visualized statistic that is physically intuitive and has proven useful in the design and analysis of underwater acoustic systems.

The present state of the theory of sea surface sound is such that the model development is necessarily experimentally based.[1] While several measurements of the directivity function have been made, it has proven difficult to make this measurement in such a way that the near horizontally directed energy is not significantly affected by long-distance sources that complicate the modeling process.[2] A theme in the data processing, which I will describe, is that having the total directional spectra determined by the local sea surface condition allows one to partition the measurement into more than a single source type because the source types distinguish themselves by their directional patterns.

The approach this project took was to build a database of directional spectra measured in an acoustically isolated area where the acoustic ambient is dominated by the local sea conditions.

PROJECT OBJECTIVE

- Develop Model Of Acoustic Ambient Vertical Directional Spectrum Due To Sea Surface Sound.

PROBLEM STATEMENT

- Present Directional Spectrum Measurements Frequently Contain Long-Distance Sources Which Complicate Modeling Process.

PROJECT APPROACH

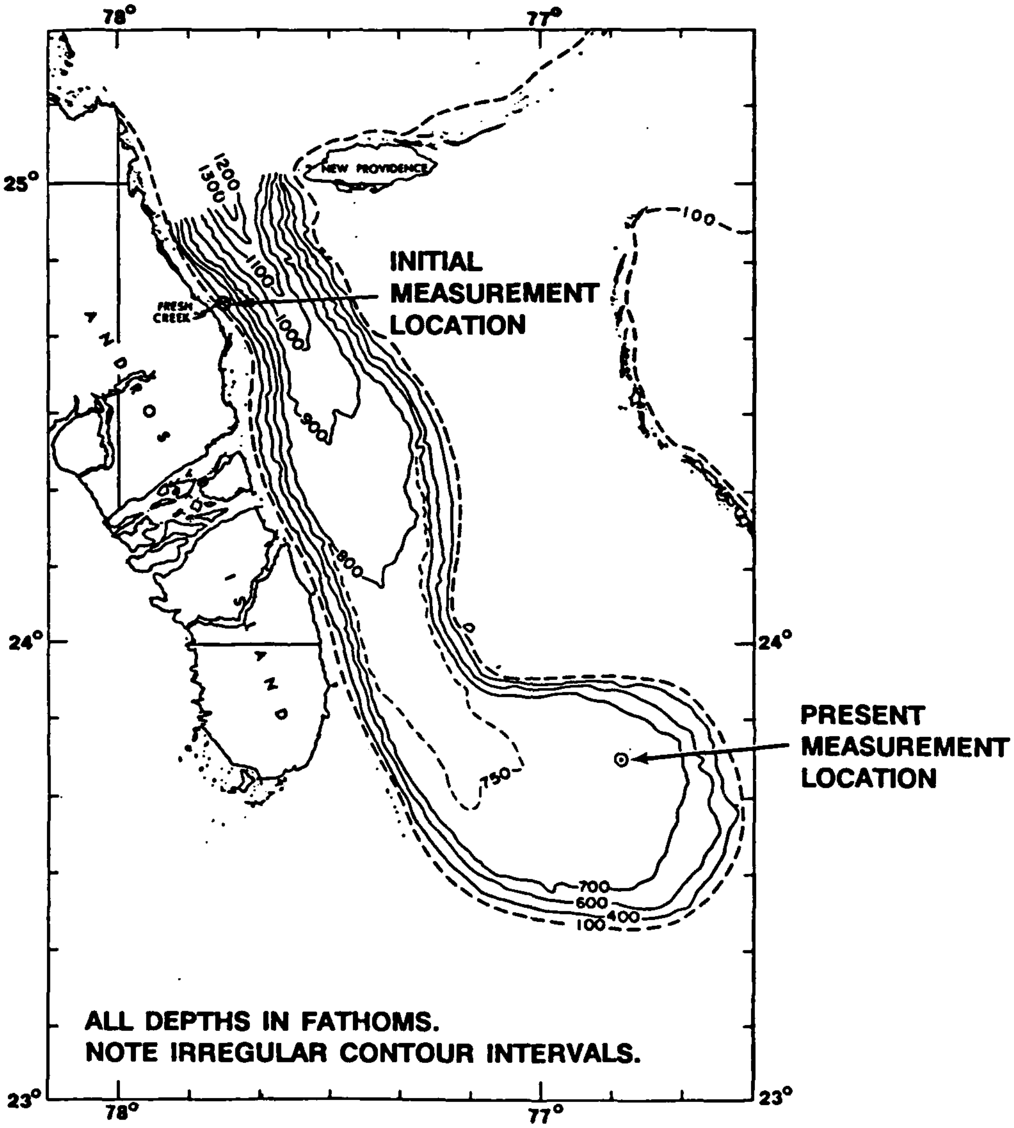
- Accumulate Database From An Acoustically Isolated Area With It's Acoustic Ambient Dominated By Well Documented Local Wind And Sea Conditions.

SLIDE 2: (1 minute)

The Tongue of the Ocean (TOTO), The Bahamas, is the location of the measurement. It is a relatively deep water basin that is totally isolated from global shipping. This figure, with the depth contours in fathoms, shows that the shallowest area is 700 fathoms, or 1300 meters, deep. This is deep enough in wavelengths not to act as a shallow water location but shallow enough to have a lossy "bottom-limited" propagation characteristic within the basin itself. The Naval Underwater Systems Center has a presence in TOTO which makes available environmental monitoring locations and ready access to small vessels for servicing the acoustic measurement system.

Two measurement locations have been used. The initial two-month deployment of the measurement system was at a near reef-site close to Fresh Creek. The location was chosen for logistic reasons to service the initial wetting down of the system. The present location of the system is on the east side of the cul-de-sac. This location is further shielded from transiting vessels in TOTO by the land mass north of the location. Ten months of the planned one-year deploymenthave been completed. Note that the diameter of the cul-de-sac is a little more than 30 nmi.

MEASUREMENT LOCATION



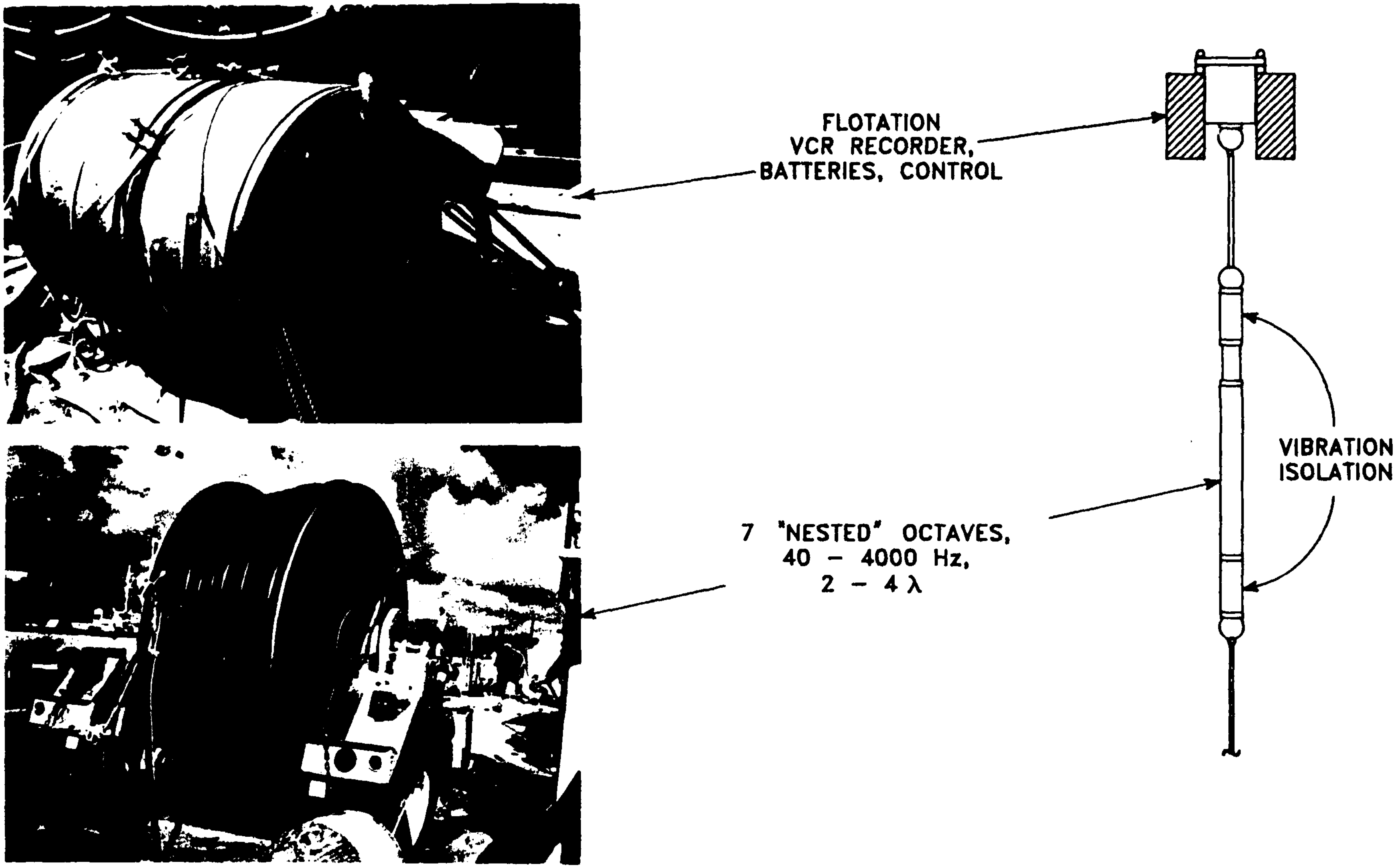
SLIDE 3: (2 minutes)

The measurement system objective was a broadband characterization of the diffuse acoustic ambient field. The Naval Underwater Systems Center IR/IED sponsor required that the system be quite low cost. The system that you see in this figure is the resulting compromise. The dilemma of the acoustic antenna design is that over much of the angular range the diffuse ambient changes slowly with vertical angle and a low-resolution system is adequate, but near the horizontal direction, where media refraction can abruptly change the solid-angle density function, a considerably higher resolution system is necessary. The fielded system covered the two-decade frequency band shown with a modest 2- to 4-wavelength aperture. A parametric spectral estimation algorithm that models the media refraction was then used to obtain the higher angular resolution near the horizontal direction.

The seven octaves are recorded sequentially by synchronously recording the eight 14-bit hydrophone signals from each section on three video cassette recorders. Also recorded are the depth and tilt of the vertical hydrophone array. After the 21-minute recording period the system sleeps for 50 hours before it repeats the cycle. Every 45 to 50 days it is necessary to retrieve the system to replenish the 3 VCR tapes and 96 flashlight batteries that power the electronics.

The brightly colored syntactic foam collar around the instrumented pressure vessel maintains the verticality of the system within a small fraction of the hydrophone array angular resolution.

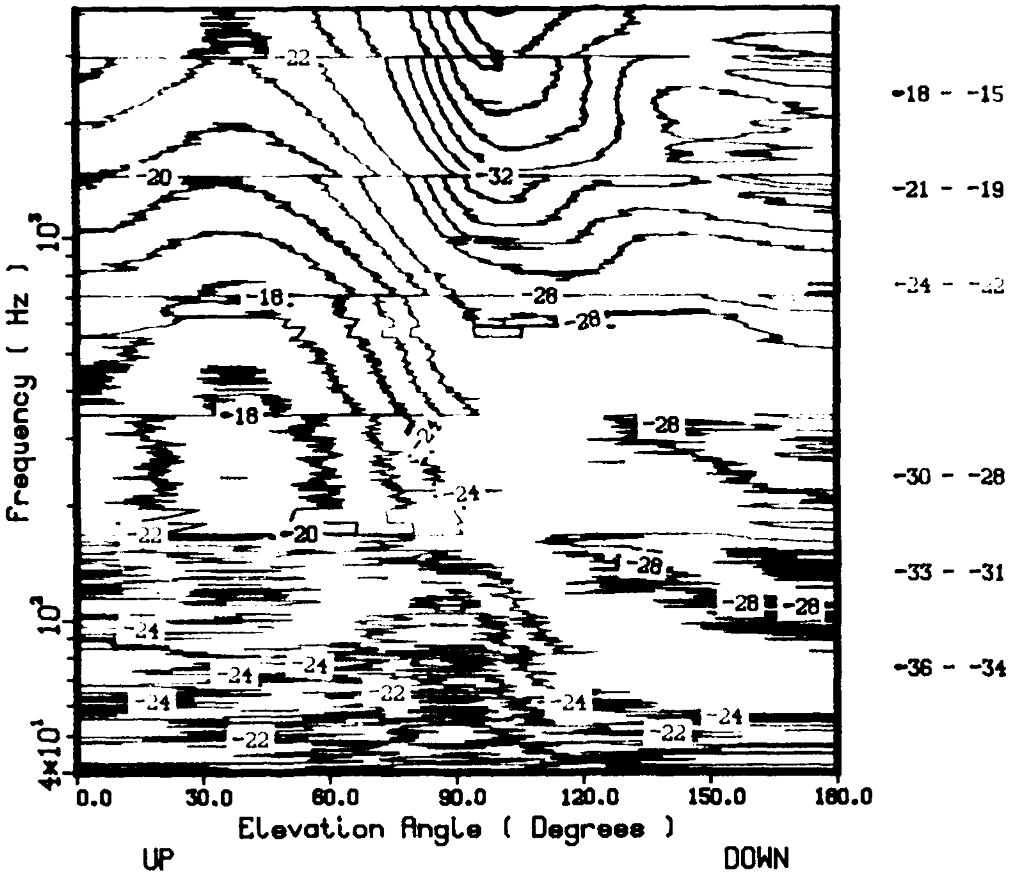
INSTRUMENTATION SUMMARY

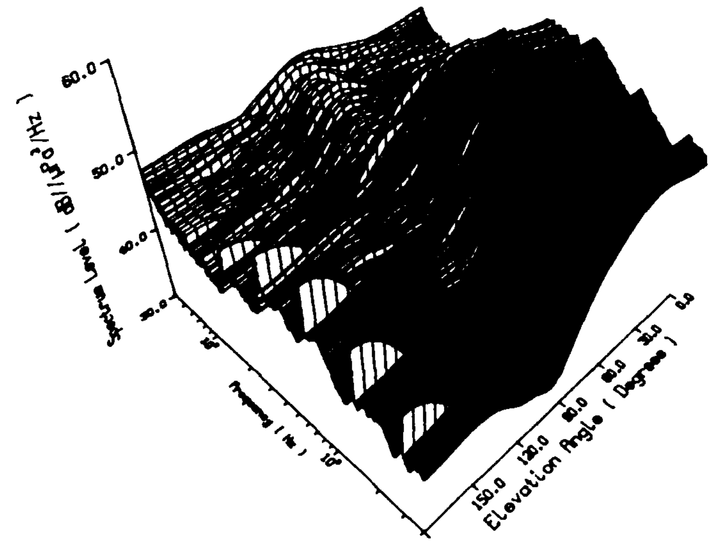


SLIDE 4: (1 minute)

The basic statistic measured is the hydrophone cross-spectral density (CSD) matrix. However, because the CSD matrix is not a readily visualized quantity, it is useful to calculate, from the CSD matrix, a beamformed output that is displayed and examined to determine the quality of each measurement. This figure illustrates the "direction of arrival spectrum" in (dB//μPa^2/Hz) as a function of frequency and elevation angle. The contour plot on the left gives quantitative details, and the surface plot on the right gives a qualitative view of the entire surface. Note that zero degrees is looking straight up at the water surface. The figure is a composite of all seven octaves; the high frequency end of each aperture is visually "flagged" by the aliasing lobe that occurs at the frequency for which the hydrophones are spaced one-half wavelength apart. Note also that in the horizontal direction, i.e., at an elevation angle of 90 degrees, a clear refractive notch is evident at high frequencies despite the low angular resolution of the measurement system.

EXAMINING RAW DATA





SLIDE 5: (2.5 minutes)

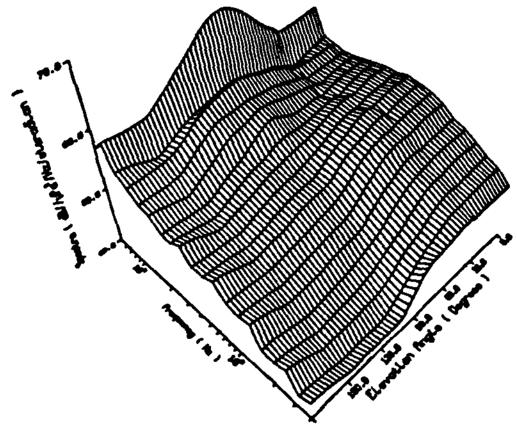
The overall characteristics of the vertical directional spectra as a function of the sea surface condition are illustrated here. These figures represent first-order estimates of the directional spectrum formed by simply normalizing the beamformed output by the solid-angle coverage of the major lobe and then averaging the spectral levels over one-third-octave bands. The ordinate of these figures is the directional spectrum in (dB//μPa^2/Hz/steradian). The two independent variables are again frequency and elevation angle, with zero degrees looking up at the water surface. Except for the refractive "notch" area surrounding the horizontal direction, these first-order estimates are quantitatively quite correct and were obtained in the initial near-reef deployment. Higher order estimates of the directional spectra will be discussed shortly but are not necessary for the present discussion.

The measurement used to describe the sea surface condition is a nondimensional surface friction velocity.[3] Wind speed measurements made 10 meters above the water surface were converted to surface friction velocity and then nondimensionalized by the minimum phase velocity of the water surface capillary-gravity wave field. A unity value of the nondimensional friction velocity is interpreted as the point of incipient whitecapping.

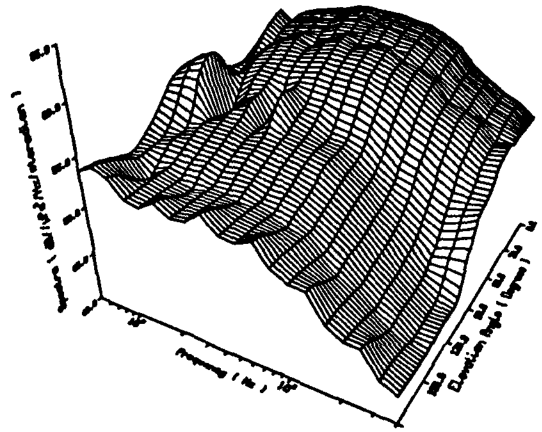
The following aspects of the data should be noted. First, with whitecaps present the measured vertical directional spectrum in the direction of the sea surface is a smooth surface with a rather flat maximum in the direction of the surface at 500 Hz. This surface extends over the entire frequency range of the measurement. Second, without whitecaps present but with nondimensional friction velocity greater than one-half, the shape of the measured directional spectrum surface above its maximum value at 500 Hz remains unchanged although the height of the surface falls with the third power of the friction velocity. Below 200 to 400 Hz the surface falls rapidly with a reduction in frequency. Third, with the nondimensional friction velocity less than one-half, the measured directional spectrum is dominated by the modal behavior of the TOTO channel, not the local sea surface; i.e., the sea surface radiation is no longer being measured. Fourth, below 100 Hz the data are frequently contaminated by "tones" radiating over a large horizontal extent of the escarpment. The last observation is characteristic of the near-reef site data only.

DIRECTIONAL SPECTRA WITH WHITECAPS PRESENT

$u_*/u_c = 1.18$

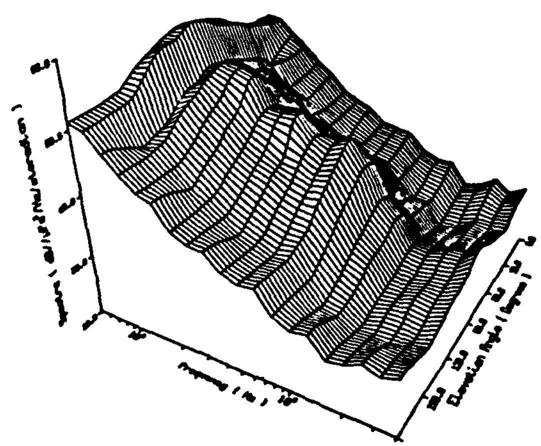


$u_*/u_c = 1.81$

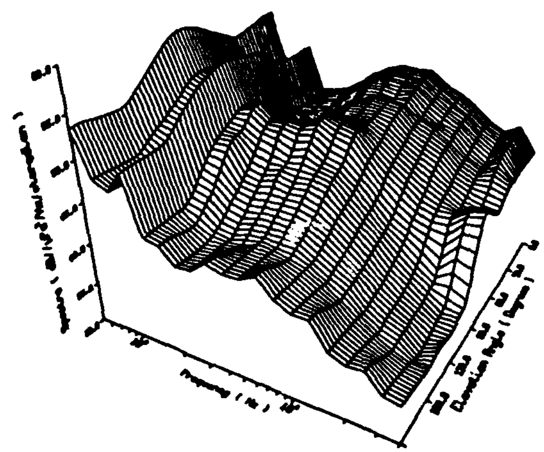


DIRECTIONAL SPECTRA WITH NO WHITECAPS PRESENT

$u_*/u_c = 0.32$



$u_*/u_c = 0.68$



SLIDE 6: (3 minutes)

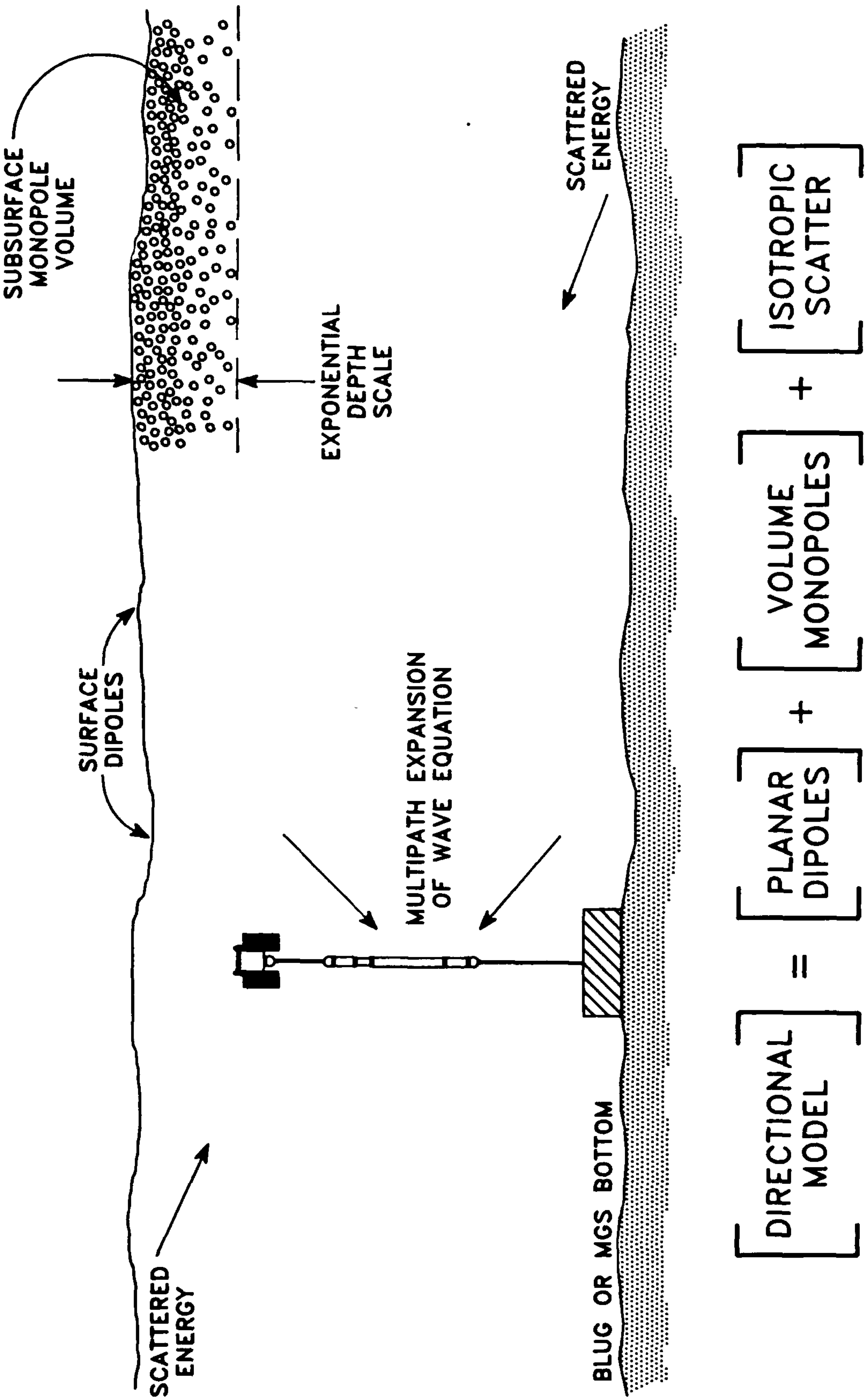
There are three reasons for choosing a parametric spectral estimation approach. First, if an appropriate bases function set exists then quite efficient parameterization of a complex field variable statistic is possible. Second, an increase in spectral resolution over nonparametric algorithms is possible. Third, physical interpretation of data can be enhanced if physical interpretation of the model is possible. For all these reasons, a model fit to the data was attempted. The model development is ad hoc and the components of the model occur historically in the acoustic ambient literature. This illustration is an attempt at quickly summarizing the ingredients of the model-fitting procedure. The actual mathematics are very straightforward.

All three of the components pictured, or at least some modified version of them, have been used individually in other studies.[4,5] What is unique to the present approach is that more than one source type is assumed present and the data are then used to assign a strength to each one individually. The three components are (1) a plane of statistically independent vertical dipoles located at the sea surface, (2) a volume of statistically independent monopoles exponentially distributed in depth below a smooth pressure release surface, and (3) an isotropic term intended as a "catchall" component to include such things as scattering from media nonhomogeneities. The first two sources are propagated to the receiving system using a multipath expansion of a wave equation solution. This allows the modeled terms to be given an angular distribution. This was realized using the "generic sonar model" software package. Depending on the frequency, either BLUG or MGS bottom loss values were used. The effects of the hydrophone spatial sampling and finite aperture are included in the model.

The parameters representing the source area density occur linearly in the model, and the exponential depth scale occurs nonlinearly. Because the volume and surface source terms become indistinguishable from each other as the depth scale goes to zero, an iterative parameter estimation scheme was used to ensure orthogonality in the parameters. The result is that a volume source term becomes significant only if the depth scale is of the order of a wavelength or greater.

Note also that if a contaminating plane wave is present in the data it also is readily accounted for in the fit to data but is ignored in the reconstruction of the directional spectrum.

PARAMETRIC MODEL SUMMARY



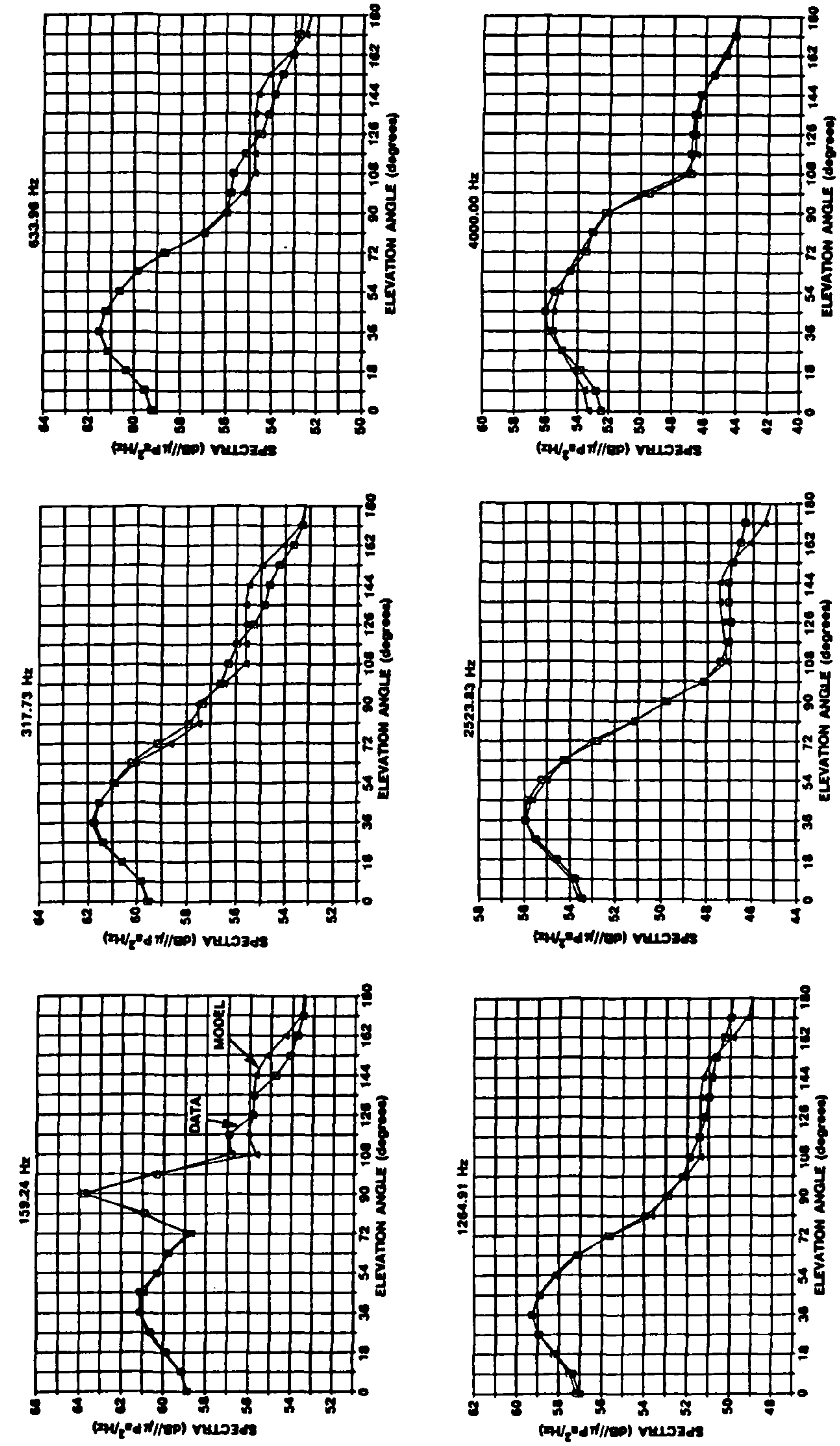
SLIDE 7: (1 minute)

An important indication of the quality of the model is how well it fits the data. This figure shows an example of the model-data comparison at the beamformed output. In each panel the abscissa is the elevation angle steered to and the ordinate is the beamformed output. In the direction of the surface, i.e., between 0 and 90 degrees, which is the process we wish to model, the fit is nearly always within 1 dB of the data. The standard error for the "fit to data" as well as the standard error of parameter estimates is typically less than 5 percent. The cross-correlation coefficient between parameter estimates is always less than one-tenth.

Note that in the upper left-hand panel there existed a "target", i.e., a plane wave contaminating the data. A plane wave component added to the model readily fit the data.

MODEL-DATA COMPARISON

$u_x/u_c = 1.8$

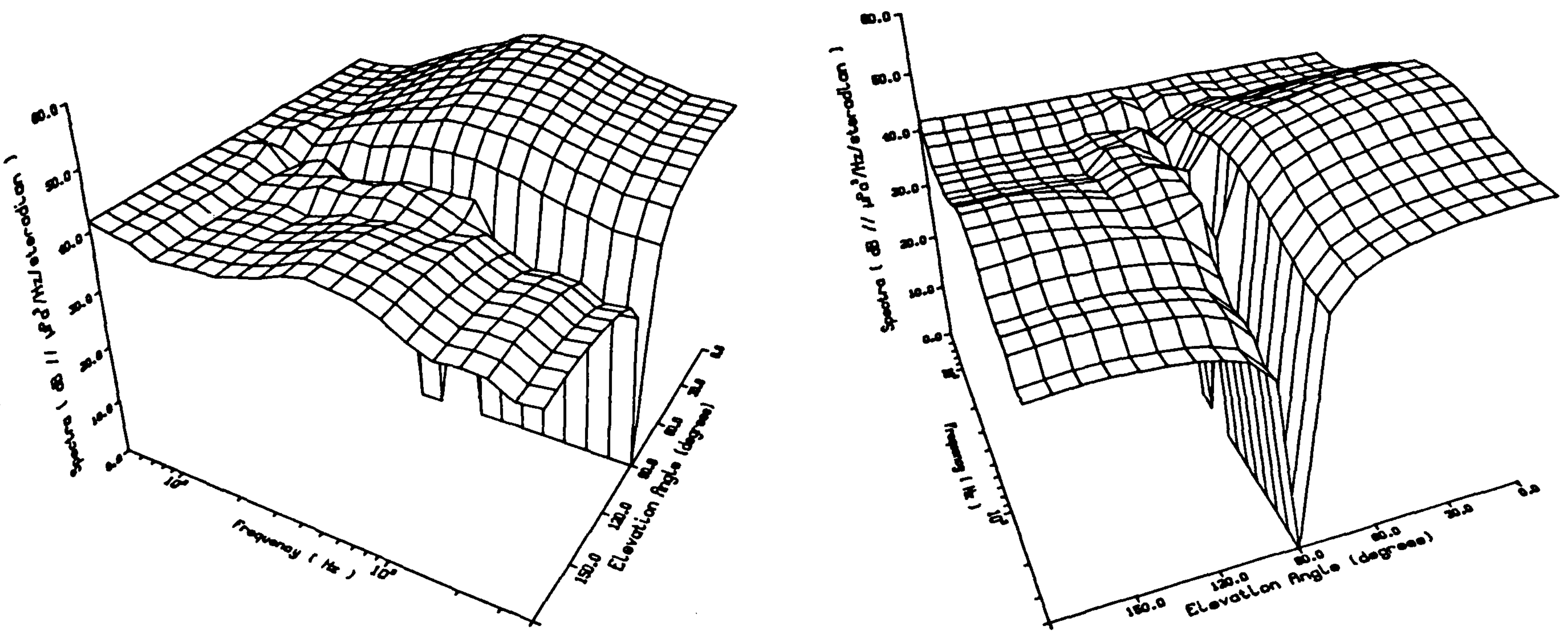


SLIDE 8: (3/4 minute)

This figure shows an example of a measured vertical directional spectrum employing the parametric spectral estimation described. The measurement is from the cul-de-sac deployment with no whitecaps present. As before, the ordinate is the solid-angle density function illustrated as a function of log frequency from 40 to 4000 Hz and elevation angle from straight up to straight down. The direction of the sea surface is on the right-hand side. The refractive "notch" with its frequency-dependent depth is quite evident. Because the notch depth increases with frequency, it is most likely due to TOTO modal response rather than scattering.

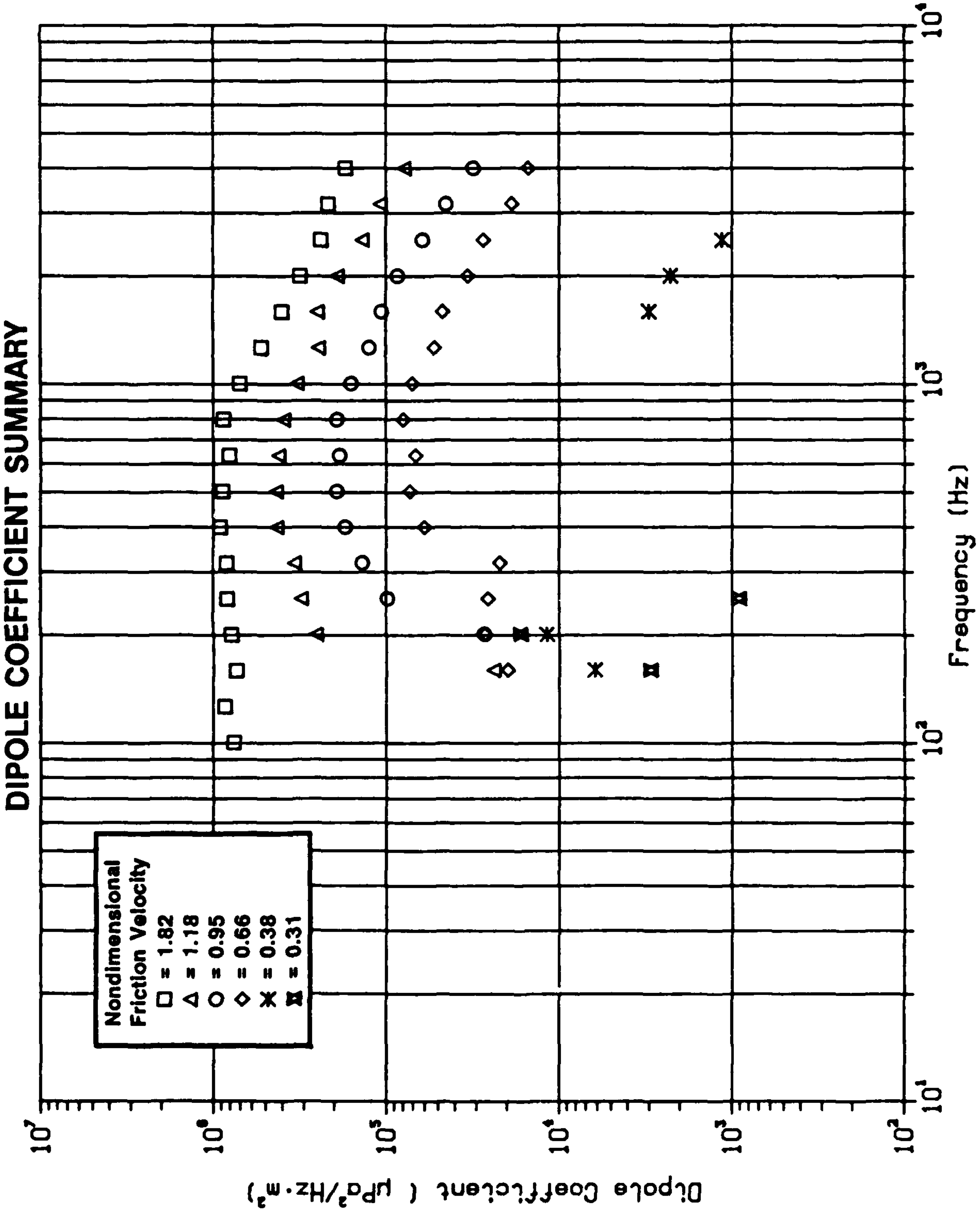
VERTICAL DIRECTIONAL SPECTRUM

$u_*/u_c = 0.83$



SLIDE 9: (3/4 minute)

In this figure I have plotted the dipole coefficient, which is a source area density term, as a function of frequency with nondimensional friction velocity as a parameter. The following two characteristics are worth noting: First, for nondimensional friction velocity greater than one-half, the source density is inversely dependent on the first power of frequency above 1 kHz and independent of frequency below 1 kHz until a lower frequency cutoff is reached. The source strength is proportional to the third power of the friction velocity without whitecaps and the second power with whitecaps. The second observation is that for nondimensional friction velocity less than one-half, either the source strength is falling faster than the third power of the friction velocity and is below the background level, or the dipole component is only erratically present.


DIPOLE COEFFICIENT SUMMARY
Nondimensional
Friction Velocity
□ = 1.82
△ = 1.18
○ = 0.95
◇ = 0.66
✱ = 0.38
⌘ = 0.31
Frequency (Hz)
Dipole Coefficient (μPa²/Hz·m²)
10¹
10²
10³
10⁴
10⁷
10⁶
10⁵
10⁴
10³
10²

SLIDE 10: (1 minute)

I will now summarize. The objective of this project is to model the vertical directional spectra due to sea surface sound alone. The approach taken is to accumulate a database obtained in an acoustically isolated area in which the acoustic ambient is dominated by the local sea conditions. To do this, a low-cost vertical hydrophone array operating from 40 to 4000 Hz has been operating in the Tongue of the Ocean, The Bahamas, for over a year. A data processing system has been designed and implemented that features a particularly efficient parameterization of the measured directional spectra. The physically based parametric model used in the spatial spectral estimation process has given some anecdotal evidence of the character of the sea surface sound source structure. A statistically based examination of the data is underway. The measurement period will be completed in July of this year. So far, 140 trials have been recorded.

SUMMARY

- Low-Cost Broadband Vertical Hydrophone Array And Data Recording System Designed And Installed In An Isolated Area.
- Data-Processing System Designed And Implemented To Efficiently Process Data Sets.
- Unique Database (>140 Data Sets) Accumulating To Examine Statistics Of Sea Surface Sound Source Structure.
- Physically Based Parametric Model Used To Improve Angular Resolution Of Directional Spectra.

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3. B.R. Kerman, "Underwater Sound Generation by Breaking Waves," Journal of the Acoustical Society of America, vol. 75, 1984, p 148.

4. J.E. Ffowcs Williams and Y.P. Guo, "Mechanisms of Sound Generation at the Ocean Surface," Sea Surface Sound, edited by B.R. Kerman, Kluwer Academic Publishers, Boston, MA, 1988.

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