THE DETECTION OF FISHES AND CETACEANS USING THE VECTOR SOUND-INTENSITY PROBE

Kenneth D. Ekstrom and Clifford A. Goudey

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Center for Fisheries Engineering Research
MIT Sea Grant College Program
Bldg. E38-370, 292 Main Street
Cambridge, MA 02139

Sea Grant College Program
Massachusetts Institute of Technology
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Kenneth D. Ekstrom, Principal Investigator
Laboratory for Acoustic Analysis
1135 Saratoga Street, East Boston, Massachusetts 02128

Clifford A. Goudey, Project Director
Center for Fisheries Engineering Research
MIT Sea Grant Program, Room E38 - 372
292 Main Street, Cambridge, Massachusetts 02139 - 4307

Abstract

We surveyed typical sounds of fishes and cetaceans and implemented detection of their finbeats and ensonifications using the fast fourier transform (FFT) to discern characteristic spectral patterns. Continuous swimming is shown by stationary signals while darting and veering cause narrowband transients in the extra low frequency band. Dolphin and whale finbeats, pulse bursts and calls are displayed on a spectral scale. The vector sound-intensity probe (VSIP) is analyzed for its viability as a broadband localization sensor of these signals. It suppresses isotropic ocean noise and can detect fading multipath signals unsensed by conventional arrays which rely on the sound pressure (potential energy of the acoustic field diversity). When signals have substantial kinetic energy (particle velocity) with negligible potential energy (pressure in deep fade), intensity or particle velocity sensors are necessary for their detection in the acoustic channel. The VSIP yields azimuth and pitch of individual spectral features and can function as a robust tracking receiver for autonomous underwater vehicles (AUVs) and autonomous surface craft (ASC).

Introduction

The need for marine animal detection and localization is well established in the international community of environmentalists, fishermen, marine biologists, icthyologists, engineers and scientists [1, 2]. Active sonars offer range and flexibility using high power beamforming arrays and doppler detection [3] while passive sonars require subtle digital processing techniques in order to extract low level signals from high level noise. Fishes are known to emit sound due to bone stridulation, muscle contraction and hydrodynamic turbulence [4] but little appears in the literature that describes the detection of extra low frequency finbeat energy emission in a satisfying manner. To fill this gap we set out to test the acoustic pressure field and flow in fish tanks for evidence of finbeats using an infrasonic hydrophone. Our general motivation is to survey the range of fish and cetacean sounds for detection and characterization purposes.

Natural selection has adapted marine animals for diverse swimming dynamics in the course of evolution. Metabolic energy powers the animal to swim fast enough for the next catch. That catch perpetuates the process. Efficient as it is the caudal fin is much smaller than the wavelength of the signal generated and energy transfer to the water is minimal. However, very low frequency sound sees low absorbtion in water making a hypothetical scenario of low amplitude tailbeat compression pulses propagating substantial distances. In this regard a school of migrating tuna could generate a power flux measurable in the acoustic channel using a vector sound intensity probe (VSIP) if certain conditions are met.

This need for detection methodology has been strongly emphasized by the Atlantic Offshore Cetacean Take Reduction Team. This NMFS sanctioned group is preparing recommendations for the pair trawl, longline and driftnet tuna fisheries. Current levels of cetacean injuries and mortalities threaten to impact these important fisheries [5]. At sea detection techniques are useful to approach zero-bycatch in the pelagic pair trawling industry [6]. The literature contains works which report wide bandwidth energy patterns (2 kHz) emanating from schools and individual fishes. Analysis techniques used historically have not focused on the 0 to 8 Hz band typical of large pelagic fish and marine mammal tailbeat frequencies. The investigation of this band could supply useful information for detection and hydrodynamic purposes.

Background

Acceleration and veering of fishes have shown large signals in the data which may contain evidence of the fundamental tail beat frequency [4]. Maximum reported tail beat frequencies for tuna are at 6 Hz with projected frequencies at 10 Hz based on experiments using injected electrical twitch stimuli of swimming muscles [12]. The fastest mackeral (length .305 m) filmed by Wardel and He swam with a tailbeat frequency of 18 Hz at 12° C., a stride length close to one body length and a speed of 5.5 m/sec [22]. Some authors report swimming styles that require greater power and efficient interaction between the propelling surfaces and the water that allow the fish to move twice as far for each tail beat [28].

Hog-mouth fry, *Anchoviella choerostoma* (Goode), in large schools (~1/2 acre, at sea) produce streaming sounds to a maximum frequency of 1.6 kHz with greatest magnitude occurring below 500 Hz. Angular accelerations (veering) of the school produce higher magnitude sounds to a maximum frequency of 2 kHz with most energy below 800 Hz for durations of 200 - 600 milliseconds. Moulton reports schools of 500-1000 individuals in a tank 8'x2'x1' deep (in the lab) did not produce sounds of sufficient magnitude to rise above system noise [4].

Individual yellow jack, *Caranx latus* (Agassiz), and skip jack, *Caranx ruber* (Bloch), produce transient veering sounds (thumps and volleys of thumps) of duration 50 - 60 milliseconds with spectral distribution to 1.7 kHz and most energy below 1 kHz [4]. These fishes have the stiff caudal fin structure somewhat similiar to the tuna tail. Tuna may also produce these sounds.

The normal swim cycle is sustained by a complex interaction of internally distributed muscular forces and vertabrae flexing. Alternating muscular contractions at the twitch frequency provide the distributed forces for the swim cycle of tunas and dolphins. The forces are distributed along the backbone which bends in the direction of the contraction (vertabral flexion). The cycle culminates at the peduncle (tail shank) where the power is transferred to the caudal fin or flukes delivering the power thrust to the water. Motion is along the horizontal axis for tunas and along the vertical axis for dolphins. For white-sided dolphins, peak stresses in tail muscles and their tendons, in swimming at 5.2 m/s, are calculated to be 0.32 MPa and 24 MPa, respectively [18].

Power ratings

At steady speeds a fish must produce enough metabolic power to compensate for hydrodynamic drag on its body. When accelerating additional power is required to overcome the inertia of the body mass and the increasing hydrodynamic drag in unpredictable non-linear ranges and regions. The relationship between the power (P), the swimming speed (U) and the drag coefficient (C_d) has been given as $\mathbf{P = (rho)\ A\ U^3\ C_d}$, where rho is the density and A is the body surface area [12]. The power required is roughly proportional to the cube of the velocity. Modeling of the fish swimming process is a daunting task in part due to the difficulties in solving the Navier-Stokes equation for the compressible medium in the non-linear high velocity region. For tuna, maximum power of 10 Kw is suggested for a 200 Kg fish using 75 Kg muscle on alternate sides for the duration of a short burst [12].

The wetted surface of the tail fin imparts distributed force vectors to the contiguous water molecules for propulsion imparting flow and in some cases shedding a vortex. It is hypothesized that successive elastic impacts of the tail fin cause propagation of minute compressional waves whose constituents consist of pressure and particle velocity (potential and kinetic energies). This may occur when the tailbeat frequency increases to high rates.

Navier-Stokes Equation

The following statement by G. G. Stokes [23] in 1868 seems to fit the case of reciprocating tailbeats and addresses the physics of transition from flow to sound waves. It is the existance of this transition point that we investigate in order to determine the likelihood of detection (or sensibility) in the domain of time varying pressure and particle velocity waves.

"When a body is moved to and fro in any fluid, the fluid behaves almost exactly like an incompressible fluid, and there is merely a local reciprocating motion of the fluid from the anterior to the posterior regions, and back again in the opposite phase of the body's motion, in which the region that had been anterior becomes posterior. If the rate of alternation of the body's motion be taken greater and greater, or, in other words, the periodic time less and less, the condensation and rarefaction of the fluid, which in the first instance was utterly insensible, presently becomes sensible, and sound waves (or waves of the same nature in case the periodic time be beyond the limits of audibility) are produced, and exist along with the reciprocating flow. As the periodic time is diminished, more and more of the encroachment of the vibrating body on the fluid goes to produce a true sound wave, less and less a mere local reciprocating flow. For a given periodic time, and given size, form, and mode of vibration of the vibrating body, the fluid behaves so much the more nearly like an incompressible fluid as the velocity of propagation of sound in it is greater."

The momentum conservation equation (Navier-Stokes equation) is given by Teman [29] as

$$\rho \left(\delta u / \delta t + \sum_{i=1}^{3} u_i \, \delta u / \delta x_i \right) - \mu \Delta u - (3\lambda + \mu) \, \mathbf{grad\ div}\, u + \mathbf{grad}\ p = f$$

where $\mu > 0$ is the kinematic viscosity, λ wavelength, and $f = f(x, t)$ represents a density of force per unit volume. The compressiblity term $(3\lambda + \mu)$ **grad div** u governs the frequency dependency of the propagation of sound.

Materials and Methods

The data acquisition system is configured for ease and speed of deployment and is DC powered for use in remote locations. The system ground is referenced to the seawater potential. When available AC powering is implemented for continuous operation and recharging.

A Benthos RDA (reduced diameter) streamer hydrophone with frequency response of 2 - 2000 Hz +/- .5 dB is preamplified, prefiltered, sixth order Butterworth filtered (rolloff: -36dB/octave), post filtered, and sampled at 16 and 32 samples per second by a 12-bit PCMCIA A/D convertor interfaced to an AST notebook computer. Data is written to 9600 and 19200 byte files on the disk drive. These files are processed by 512 point FFT's [21] (Bartlett window) and are graphically displayed as time series and spectral energy distribution [20]. Resolutions of the frequency bins are 15.625, 31.25 and 125 milliHz.

The signal from the Benthos RDA hydrophone (Lead Zirconate Titanate - PZT) consists of pressure, aeolian flow noise, acceleration, and electromagnetic field components, i.e. **s(t) = p(t) + fl(t) + a(t) + em(t)**. The flow acceleration signal is eliminated by making the hydrophone stationary. The biggest em component is at 60 Hz, above the primary analysis range. There does exist the possibility that limited range electromagnetic signals are being radiated by the fishes's central nervous systems including muscle twitch signals that control the finbeat and heartbeat frequencies [12]. Electromagnetic attenuation in sea water = 6×10^{-2} dB / meter at a conductivity of 4 mhos/meter at 4 Hz [25]. See figure 2 on Page 8.

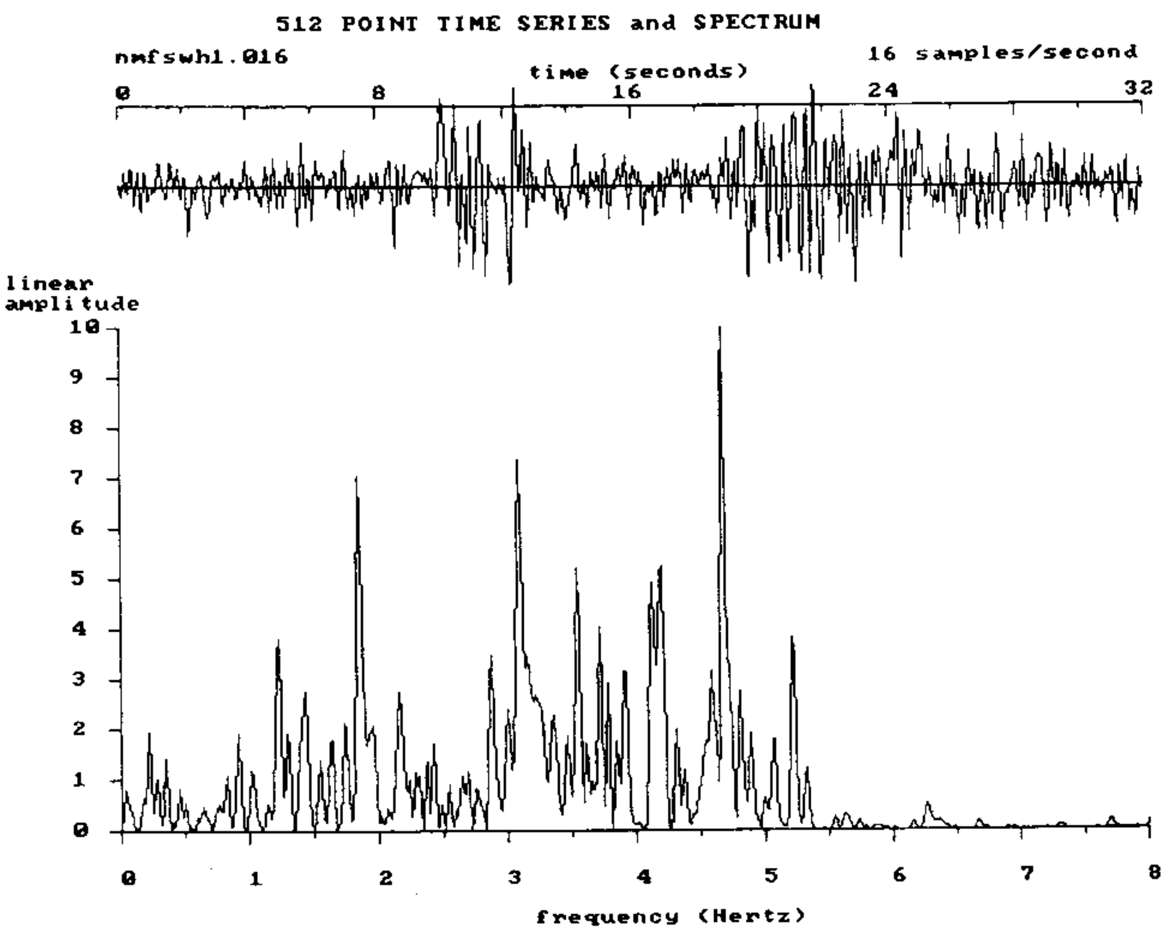
The data acquisition software was programmed using a 16-bit compiler (Turbo C++) and the data processing software was programmed using a 32-bit compiler (Watcom 9.5). Further work on the finbeat detection system is needed to test detection distance, calibrate amplitudes, and differentiate tunas and dolphins using the quadratic detector [9].

Most of the fishes observed were swimming at .5 to 4 tail beats per second and the primary tailbeat analysis range was designated as 0 - 8 Hz in order to achieve fine resolution (narrower bandwidth implies finer resolution). Control ambient data runs were made in tanks and buckets without fishes to see what spectral features were contributed by floor coupled tremors and circulation pumps. Within the scope of this study the emphasis is on finbeat frequency measurement and frequency calibration. Spectral amplitudes are shown as relative linear values with the largest normalized to 10.

Results

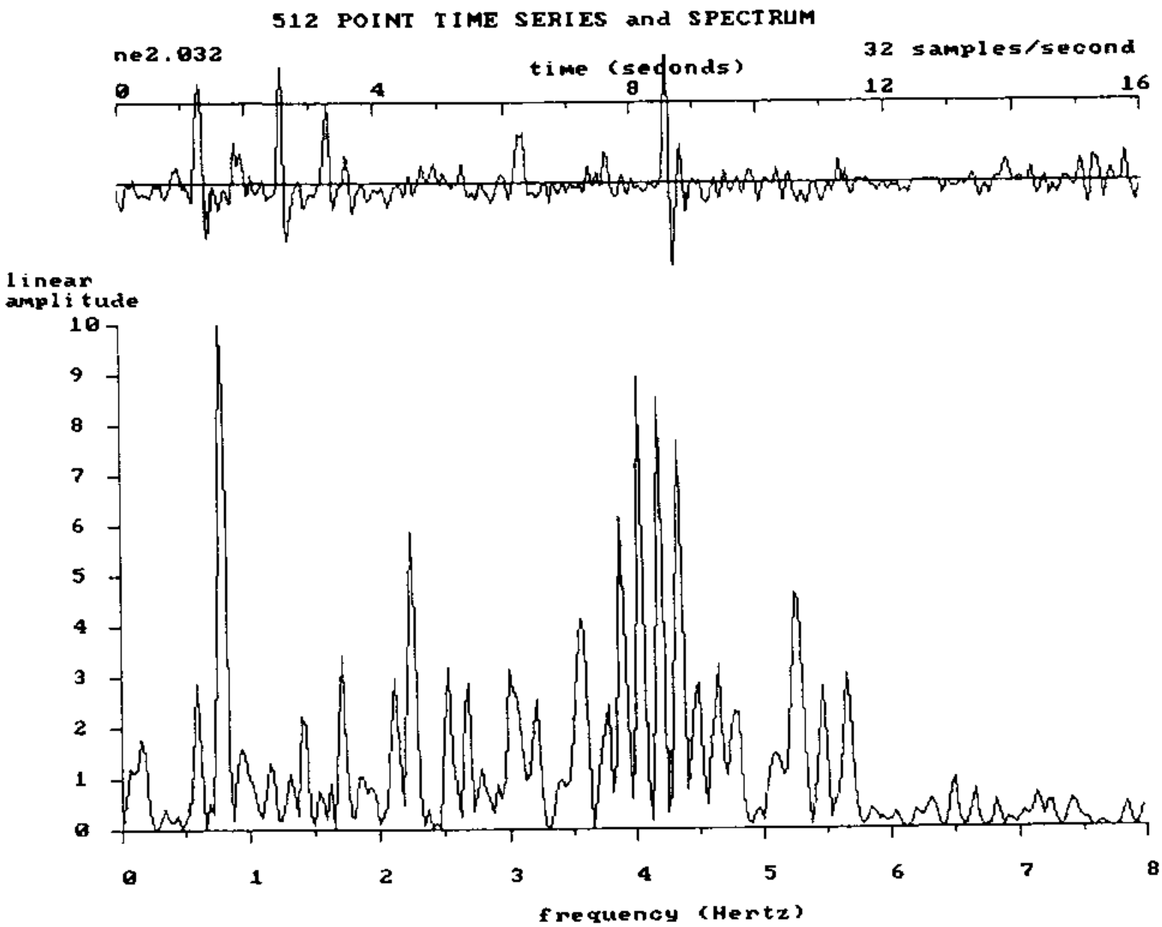
National Marine Fisheries Service Aquarium, Woods Hole, Massachusetts
September 16, 1996
Tank A: 4 striped bass, 2 bluefish, 6 permit, 1 tautog, 2 flounder and 10 blue runner.

nmfswh1.016, September 16, 1996, 1140-1150 hrs. total data acquisition run
The distribution of energy from .1 to 1 Hz indicates low velocity tailbeats and possibly pectoral fin movement. Energy concentrations at 1.2, 1.9, 2.9, 3.1, 3.55, 4.2, and 5.2 Hz indicate sources including tailbeats for single or groups of fishes. 1.2 and 4.2 Hz show up in **nmfswh4.016**. (See Appendix) The largest peak at 4.7 Hz is most likely a circulation pump. Tank resonance, water currents and foundation tremors including vortices may account for some of these signals. A stationary signal at 7.7 Hz raises the possibility that some type of Schumann resonance phenomenon [19] is occurring in the tank. See **nmfswh4.016** in Appendix.



New England Aquarium, Boston, Massachusetts - Giant Ocean Tank - October 4, 1996
The hydrophone was fixed to the tank side with a suction cup to eliminate flow induced acceleration signals. It now also becomes a seismometer for tank-coupled earth tremors. The sampling rate has been doubled to 32 samples per second and the cutoff of the antialiasing filter increased to 14 Hz in order to eliminate rolloff supression of spectral features from 5 to 8 Hz. The 512 point analysis frame size thus represents 16 seconds of data for each spectrum shown. More than one hundred different species of fishes are contained in the cylindrical 200,000 gallon giant ocean tank. This diversity is reflected in the plethora of spectral spikes shown in the data.

ne2.032 - 1212-1217 hrs. total data acquisition run
Triggerfish, tuna and barracuda were making close passes (6" - 12") by the hydrophone as they swam around in formations of 1 to 5 fishes. A large stationary signal is shown at .8 Hz. This might be a preferred finbeat frequency if it is not a tank resonance. Throughout the record, pressure and flow energy peaks are shown from 1 to 6 Hz representing the diversity of swimming motions in this community of fishes. The four evenly spaced spectral peaks from 3.9 to 4.3 Hz may represent an accelerating fish. Clusters of spikes designate various swim patterns.

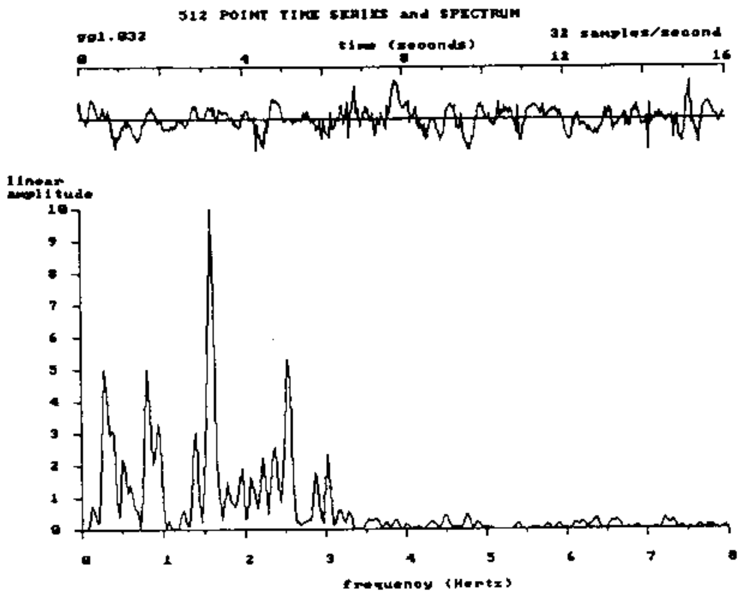


The following cetacean data (**gg1.032, mnla1.032, svt9.128, svt9a.128, mn3.128, toto4.128**) were drawn from archives of analog magnetic tape.

New England Aquarium - Vessel "Discovery" May 28, 1981

gg1.032 - Grampus gresius - Risso's dolphin "Louisiana Lu"

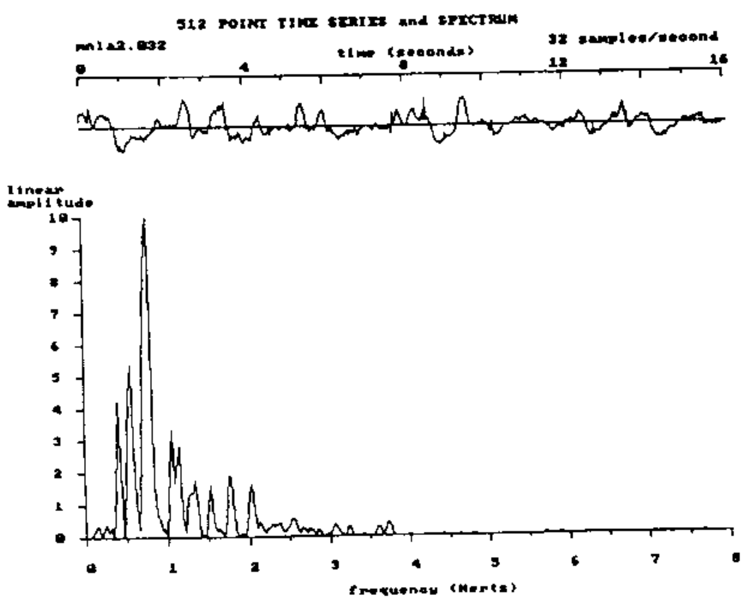
These signals were concurrent with periodic bursts of shot noise and sustained cackling from "Lu". "Lu" came ashore at Quincy and eluded capture beneath and around the LNG tanker, Lousiana. Finally netted she was in captive care for several months and was subsequently flown to a Navy facility in Hawaii. A flourish of activity is shown by spectral energies at .3, .8, 1.6, 2.5, and 3 Hz.



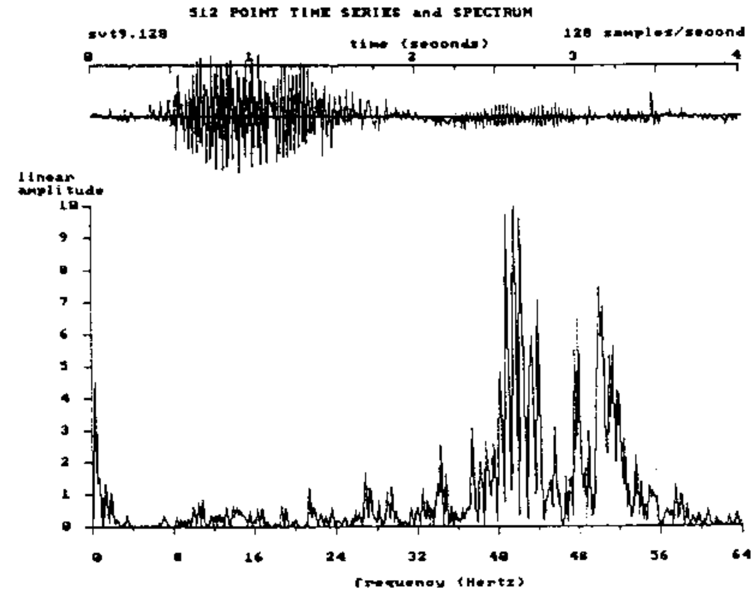
On the Sloop *Quicksilver* - August 4, 1981 - Stellwagen Bank, NW

mnla1.032

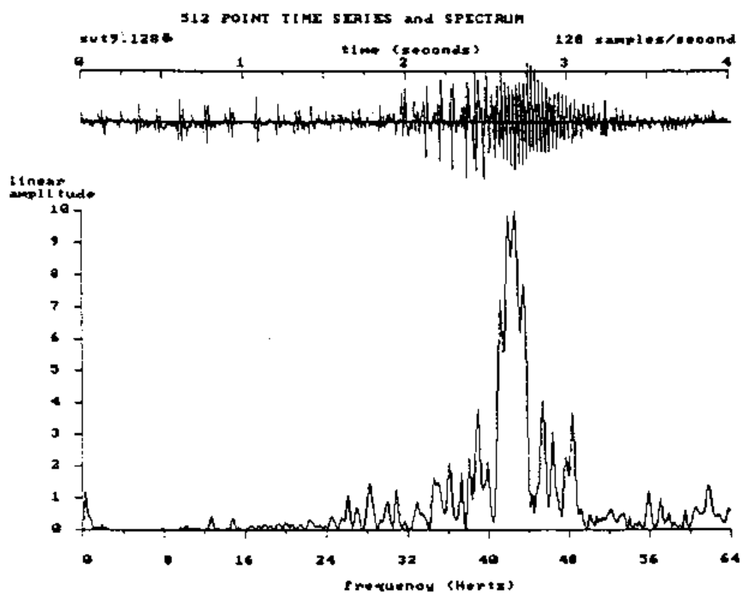
The humpback whales were vocalizing and tailslapping during this sequence of spectra. White sided dolphins were in the area. The increasing triple spike sequence from .4 to .8 Hz could be an accelerating humpback. The five spikes from 1 to 2 Hz may an extension of that acceleration. The uniformity of the last four spikes is indicative of a sustained amplitude at an increasing finbeat frequency.



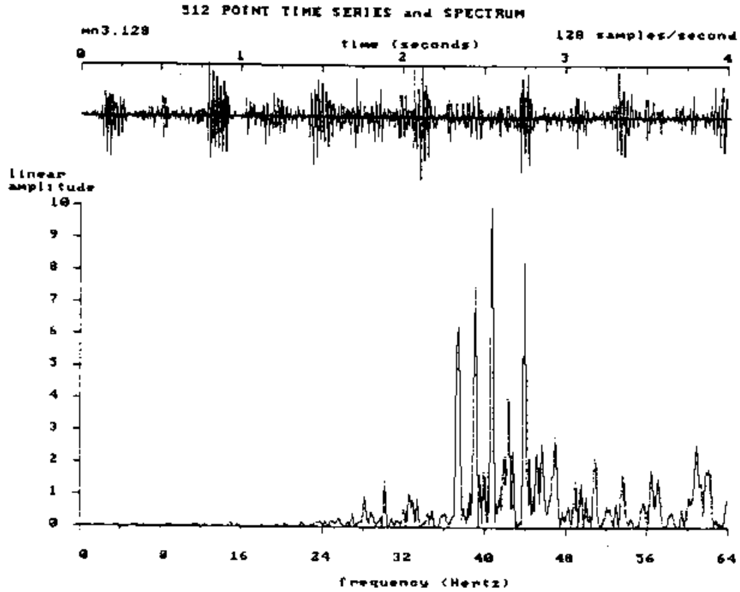
Fishing Vessel *Sea Venture*, September 16, 1990, 0730, Gulf of Mexico 24° 47' N, 82° 26' W
svt 9.128 - sample rate = 128 sps
These data represent collective pulse trains from a pod of dolphins in the Gulf of Mexico. The clicks are individual ultrasonic pulses centered at 25 KHz for the typical bottlenose dolphin. The repetition rates are at discrete frequencies from 38 to 44 Hz. 48 Hz shows a strong spike and a distribution of repetition rate energy extends from 49 to 56 Hz.



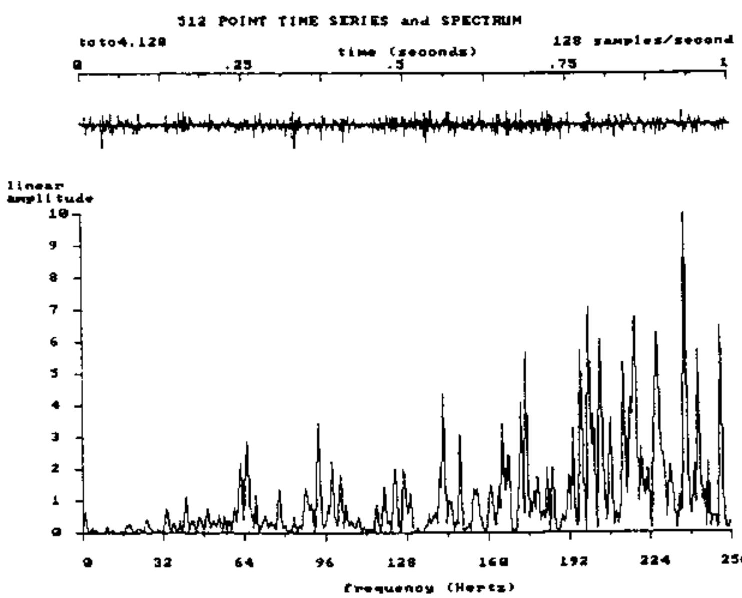
svt 9.128a - sample rate = 128 sps
There is an almost continuous distribution of repetetion rate frequency from 40 to 44 Hz wheras in **svt9.128** the repetition rates are at discrete frequencies from 38 to 44 Hz. This represents group pulse bursting activity.



On the sloop Azubah, August 16, 1982, Stellwagen Bank, Boston Entrance (BE) buoy, 0120-0153
mn3.128 - sample rate = 128 sps
Distant pulsations in the range from 35 to 47 Hz are thought to be periodic choruses from Finback whales. These are heard in the darkness when the whales may use these sound: to keep track of each other's location.



Tongue of the Ocean, Andros Island, Atlantic Undersea Testing and Evaluation Center,23April 1978
toto4.128
This recording of sperm whale click trains was made on a Sangamo 14 track recorder at 120 inches/second and transferred at 30 inches/second to a cassette at 1 7/8 inches per second. Spiked clusters centering at 32, 64, 96, 128, 144, 176 Hz, and increasing upwards from 192 Hz indicate a rich textural distribution of click energy structures.



Discussion

The time series representations (TSR) and spectral density plots (SDP) of these data are composites of four identifyable signals: pressure, flow(aeolian), electromagnetic field and acceleration on the hydrophone. They are superposed according to $s(t) = p(t) + fl(t) + em(t) + a(t)$. As such there is some ambiguity in the interpretation of the data. Mechanically induced cable noise and fishrub signals are disregarded.

The pressure signals are subject to absorbtion, geometrical spreading and multiple reflections. The absorbtion attenuation is shown in figure 1. For comparison purposes attenuation of an electromagnetic field is shown in figure 2.

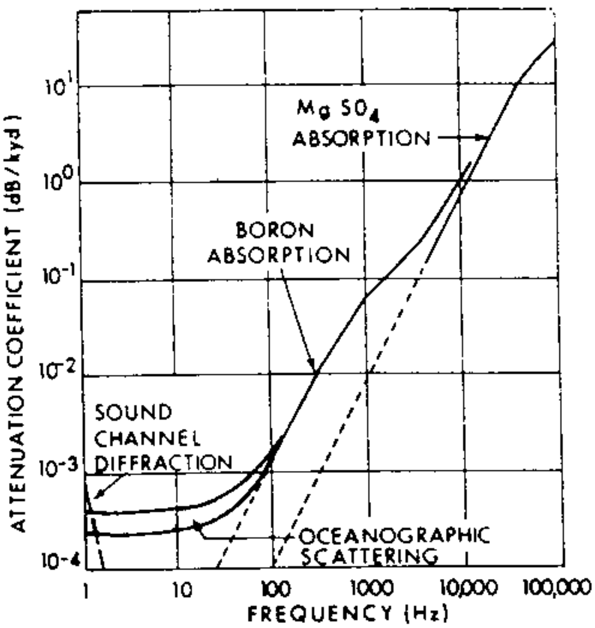


Figure 1. Sound attenuation in the ocean[24].

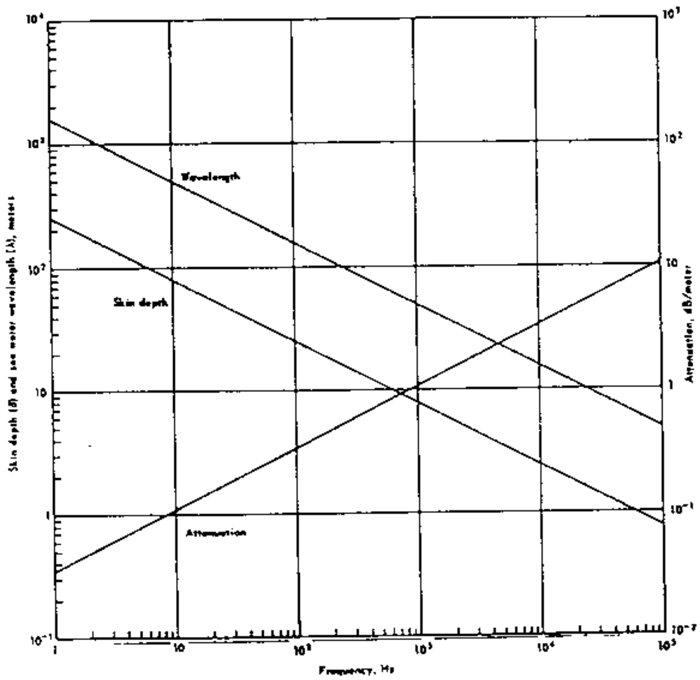


Figure 2. Electromagnetic attenuation, skin depth and wavelength in the ocean [25] (conductivity = 4 mhos/meter).

At low frequencies sound absorbtion is due to the magnesium sulfate and boron relaxation effect [24]. See figure 1. At extra low frequencies the absorbtion is due to scattering. This is in a non-linear region where pressure and flow signals are superposed at the output of the hydrophone. If intensity (pressure x particle velocity) can be measured in this region, more phenomena (earthquakes, ice fractures, whales) could be studied with the VSIP.

Representative ocean ambient

On the Ligurian shelf off the coast of La Spezia, for sea state 2 and wind 5-10 knots, representative ambient spectra peak to 92 dB at 2Hz and drop off rapidly to 58 dB at 5 Hz, rising to an average of ~68 dB to 100 Hz, all re. 1 microPascal in shallow water [7]. There is a relatively quiet region between 5 and 20 Hz where tuna and dolphin veering, acceleration, and sprinting signals may be detected in and above this ocean ambient.

Electrical and Acoustical Duals

To develop the case for using a VSIP for underwater localization we start by considering the parallels between electrical and acoustical energy.

$$\textbf{Electrical Energy} = \textbf{Power} * \textbf{Time} = \textbf{Voltage} * \textbf{Current} * \textbf{Time}$$

$$\textbf{Acoustical Energy} = \textbf{Intensity} * \textbf{Time} = \overline{\textbf{Pressure} * \textbf{Particle Velocity}} * \textbf{Time}$$

This applies to plane waves when pressure and particle velocity are in phase. When they are out of phase as in a multipath channel, there is an inbalance between the potential and kinetic energy of the diversity field. In a multipath channel when a pressure signal is in deep fade, it is possible to detect that signal by the kinetic energy (particle velocity) present in the field [26].

Some authors[31] advocate that source levels should be expressed in sound intensity levels (SIL), and not in conventional Sound Pressure Levels (SPL) re. 1 microPascal. This could give a better physical interpretation for a signal radiating from a source since it is based on the time averaged product of pressure and velocity, and not pressure alone. Thus it represents the composite of the potential and kinetic energy of the *acoustic field diversity* [26]. A proposed reference level for the Sound Intensity Level (SIL) is 1 Watt per square meter [31] , a power flux density.

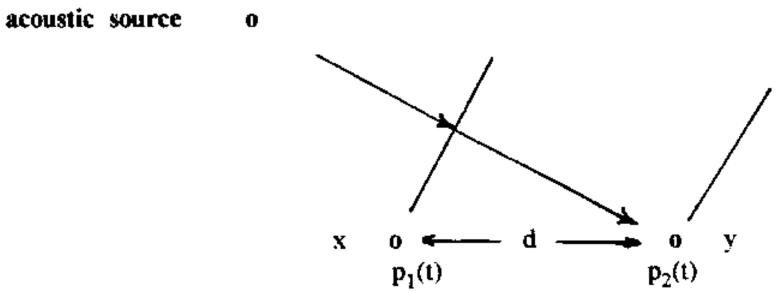
Intensity

Intensity (power flux density) measurements reveal spectral patterns that are not apparent from pressure measurements. Intensity is the time average of the product of pressure and particle velocity. Freefield measurements at sea involve different considerations (multiple ray paths increase ambiguity of interpretation of the incoming signals) than tank measurements where multiple reflections cause pressure and particle velocity to go out of phase. In contrast to conventional techniques using directional arrays and filters, the intensity approach discriminates against noise whose frequency spectra and directions of incidence coincide with that of the signal [13].

During multipath fading, signal energy is distributed between potential and kinetic fields with a time varying phase relationship. When the potential field is diminishing (marginal signal sensed by a pressure hydrophone) signal energy may be present in the kinetic field (as measured by a particle velocity sensor). Since intensity is a time average of sound pressure (potential energy) and particle velocity (kinetic energy), multipath signals obscured to pressure hydrophones by fading may be detected by velocity or intensity sensors [26].

Consider a train of plane waves impinging on two hydrophones. These waves may be seen as Fourier components of a broadband sound field, or as complex pressure representations filtered in very narrow frequency bandwidths [8].

An intensity sensor can be designed using two hydrophones at x and y separated by a distance d.



F1(omega) = FFT(p1 rms) *F2(omega) = FFT(p2 rms)*

The FFT of p1 is multiplied by the complex conjugate of the FFT of p2 and time averaged yielding the cross spectral density of energy impinging on the two hydrophones.

*G12 = time average{ F1(omega) * F2(omega)* } = Cross Spectral Density - CSD*

The negative of the imaginary part of this cross spectral density is divided by the sea water density (rho), radian frequency (omega) and the distance between the hydrophones (d). This yields the intensity as a function of omega, the radian frequency, where omega equals 2 Π times the frequency of the signal.

Intensity(omega) = - Im (G12(omega)) / rho * omega * distance = Power flux density

The preceding are the procedures used for intensity calculations in the C programming language. In order for them to be valid, the following conditions in the physical world must be met [11].

Pressure and particle velocity are related by the zero-mean-flow equation of particle motion

pressure gradient = (-) sea water density * particle acceleration

$$\delta p / \delta x = - \rho_0 \quad \delta u / \delta t$$

The pressure gradient may be approximated by the pressure difference between the two hydrophones divided by the distance between them.

pressure gradient = ~ p1 - p2 / d

provided d < lamda / 3.7 PI and 2 x d / r < .40 where r is mean distance to source and lamda is the shortest acoustical wavelength of interest. The low frequency response is limited by interchannel phase shift where the measurement error in decibels can be expressed by 10 $\log_{10}$ (1 + $theta_e$ / $theta_p$) for $theta_p$ << 1. $Theta_e$ is equipment phase shift in radians and $theta_p$ is physical phase difference in radians of the signals [15].

$$e_m = 10 \log_{10} (1 + \theta_e / \theta_p)$$

It is this measurement error that must be minimized in order to make the VSIP useful in the extra low frequency region of sound propagation.

Vector Sound Intensity Probe

The VSIP has been demonstrated by others as a viable means for direction determination in a nominal frequency range of 40 to 10,000 Hz [10, 11, 13, 14, 15]. This can differentiate multiple continuous sources by frequency and direction. The Probe uses four hydrophones to delineate azimuth and pitch of the source. At lower frequencies interchannel phase mismatch is a problem and at higher frequencies the element spacing of the probe cannot be made small enough for phase resolution using conventional hydrophones. If interchannel phase shift can be minimized in the range from 0-16 Hz, it may be useful for direction determination of finbeats at sea and for localization of transient tuna signals in that range. Frequency ranges of 90 Hz to 10 KHz and 40 Hz to 8KHz are reported for current intensity measurement systems [10].

Like the USBL system [27], the VSIP provides azimuth to target however no target mounted pinger is necessary provided the the target is emitting a sound, e.g. a thruster signature. The VSIP discriminates multipath errors in a different way than conventional directional arrays and is more sensitive to some types of fading signals [26]. The VSIP has been simulated by programming a model in the C language providing initial indication of its efficacy for projected applications.

Data Translation, Inc. and Coastal and Offshore Pacific Corp. have developed a direction estimation system for dolphins using the DT Fulcrum TI TMS320C40 DSP processor for a hull mounted adaptive beam forming system [17]. Wesmar has developed a 160 KHz trawl sonar for net scanning and horizontal look-ahead scanning. Both of these systems in use by the fishing industry use the pressure wave for detection and are fundamentally different from the VSIP.

Omnidirectional Tracking Sonar

The VSIP can be programmed to receive in range-gating mode when synchronized with a chirped-ping servo-projector to serve as an active omnidirectional sonar for surface and underwater vehicles. The echo from a target is processed by the VSIP and correlated with the transmitted pulse yielding azimuth, pitch and transfer function of the target, e.g. a tuna school. The transfer functions can be held in a look-up table (LUT) so that the program intelligence can identify the target for subsequent homing or avoidance behavior. As a passive sonar the VSIP can function as a broad-spectrum directional ear for robotic intelligence to identify characteristics of energy emitted by various sources from AUVs to dolphins. For example, in the context of an autonomous oceanographic sampling network (AOSN), this approach could detect and localize other AUVs operating in the area. The software for the VSIP sonar module can run as as an sensory input to a homing behavior module in the automatic control system. Since an autonomous surface craft (ASC) can heave to and stop its thruster motor at will to minimize self-noise, it is a natural choice for a VSIP deployment vessel with GPS, VHF radio and solar recharge capabilities. The modular tracking software can run as an input to the Mission Planning Module on the 68030 or 80486 main computer with a field programmable gate array (FPGA) operating as a sonar co-processor. Multitasking at the layered control level can be accomplished with the OS9 or QNX operating system.

Pulse Bursting Behavior of Odontocetes

Bursts of pulse energies are indicative of ultrasonic mutual scanning behavior by a pod of bottlenose dolphins during the dawn haulback of the shrimpboat Sea Venture in the Gulf of Mexico. In comparing **svt9.128** with **svt9.128a** on page 7 it can been seen that pulse rates at first at discrete frequencies from 38 to 45 Hz converge to a common rate centered on 43 Hz. This ritual of the bottlenose dolphins is not well understood and may be a basis for sonic/ultrasonic information exchange. Processing at much higher sampling rates is necessary to better understand this process.

On page 8, **toto4.128** shows a spectrum of discrete pulse bursting rates spreading from 64 to 256 Hz. These are thought to begin at a valve-like mechanism in the right nasal passage known as the museau de singe at the head of the spermaceti oil case of the sperm whale, *Physeter catodon* [30]. The pulse trains are hypothesized to be generated in a manner roughly parallel to the operation of a laser inasmuch as they both internally have reciprocating reflections of energy to pump pulse bursting at specific frequencies [32]. These specific frequencies can be used to infer size, diving rate, and identity of species of odontocetes. In the current literature a click desigates a sequence of pulses whose inter-pulse interval (IPI) is proportional to the size of the oil case in the head of the originating sperm whale, the hydrostatic pressure, and internal transfer functions of of the oil case.

Conclusions

The prototype finbeat detection system which produced the data characterizes fish fin movement in a tank and at sea for limited distances using flow and pressure signals. Further testing and detection algorithm development are necessary in order to establish the effective distances that are possible using this technique. The logical extension is to develop the VSIP for localization of stationary and transient sources in the ocean. The finbeat detection algorithms in the C programming language are adaptable for use with the VSIP. All of the signals shown in the **Results** section and in the **Appendix** are possible means by which the fishes and cetaceans may be detected and tracked using conventional hydrophones or the VSIP.

Recommendations

Further investigation of the VSIP is recommended to develop its capabilities as a general purpose sensor for detection and characterization of marine animals, vehicles, underwater earthquakes and ice fracturing. The VSIP can enhance the complement of AUV/ASC sensors to track and characterize target sources by the frequencies of their acoustic emissions in the range of 40 to 10,000 Hz and possibly lower. It can be implemented as a hotel load using Xilinx field programmable gate arrays (FPGA) for parallel processing of the baseband receiver architecture and can also function as the receiver for an active sonar. When mounted in an AUV/ASC it can discriminate incoming signals from self-noise. For optimal signal-to-noise ratios, the use of a ASC is recommended since it can heave to and silence the main thruster motor. For deep monitor of the SOFAR channel an AUV can home on ATOC sound rays using the VSIP.

Acknowledgements

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APPENDIX - Compendium of related data

National Marine Fisheries Service Aquarium, Woods Hole, Massachusetts
September 16 - 19, 1996
Tank A: 4 striped bass, 2 bluefish, 6 permit, 1 tautog, 2 flounder and 10 blue runner.

nmfswh4.016, September 16, 1996, 1252-1302 hrs. total data acquisition run
A stationary signal appears at .5 Hz, a slow sustained finbeat frequency. Signals appear at 1 Hz and sequence up to 4.6 Hz where a large clipped spike indicates a continuous circulation pump. A spike at 5.2 Hz shows a stationary signal decreasing in amplitude. The stationary signal at 7.8 Hz may be a a type of Schumann resonance. A comparable signal appears at the N. E. Aquarium in **ne3.032**.

nmfswh5.016, September 16, 1996, 1310-1320 hrs. total data acquisition run
Control - crab tank ambient made with hydrophone suspended
This shows low amplitude tremor spectral components at .75, 1.5, 2.25, 3 and 3.75 appearing to be harmonically related. The source of the fundamental at .75 Hz is unknown.

nmf1.016, September 19, 1996, 1035-1045 hrs. total data acquisition run
These data from the Tank A three days later show prominant spectral peaks at 3.3, 3.7, 4.0 and 4.1 Hz.

New England Aquarium, Boston, Massachusetts - Giant Ocean Tank - October 4, 1996

ne3.032 - 1220-1225 hrs. total data acquisition run
A large double peak at 3.5 and 3.7 Hz reflects the large excursions in the time series indicative of finbeats. Other distributed peaks extend from .2 to 5.1 Hz indicating a large variability in swimming speeds.

ne8.032 - 1252-1257 hrs. total data acquisition run
High level signals at various frequencies (.2-.9 Hz, 1.8 Hz, 2.6 Hz, 3.2 Hz, 3.7 Hz, 4.1 Hz, 4.7 Hz, 5.5 Hz) indicate energetic swimming for short durations (< 16 seconds) of time.

The following files represent some of the retro-analyzed data on standard audio casettes. The low pass filter was set to roll off beginning at 14 Hz when the sample rate was at 32 sps.

Fishing Vessel Sea Venture, September 16, 1990, 0730, Gulf of Mexico 24° 47' N, 82° 26' W

svt4.032 - sample rate = 32 samples per second
These data were taken during during close proximity of a highly vocal pod of bottlenose dolphins that were entrained by the fishing vessel following the net haulback procedure.

sv3.p32 - sample rate = 32000 samples per second
This record shows the frequency relation of a dolphin call to trawler and ambient noise.

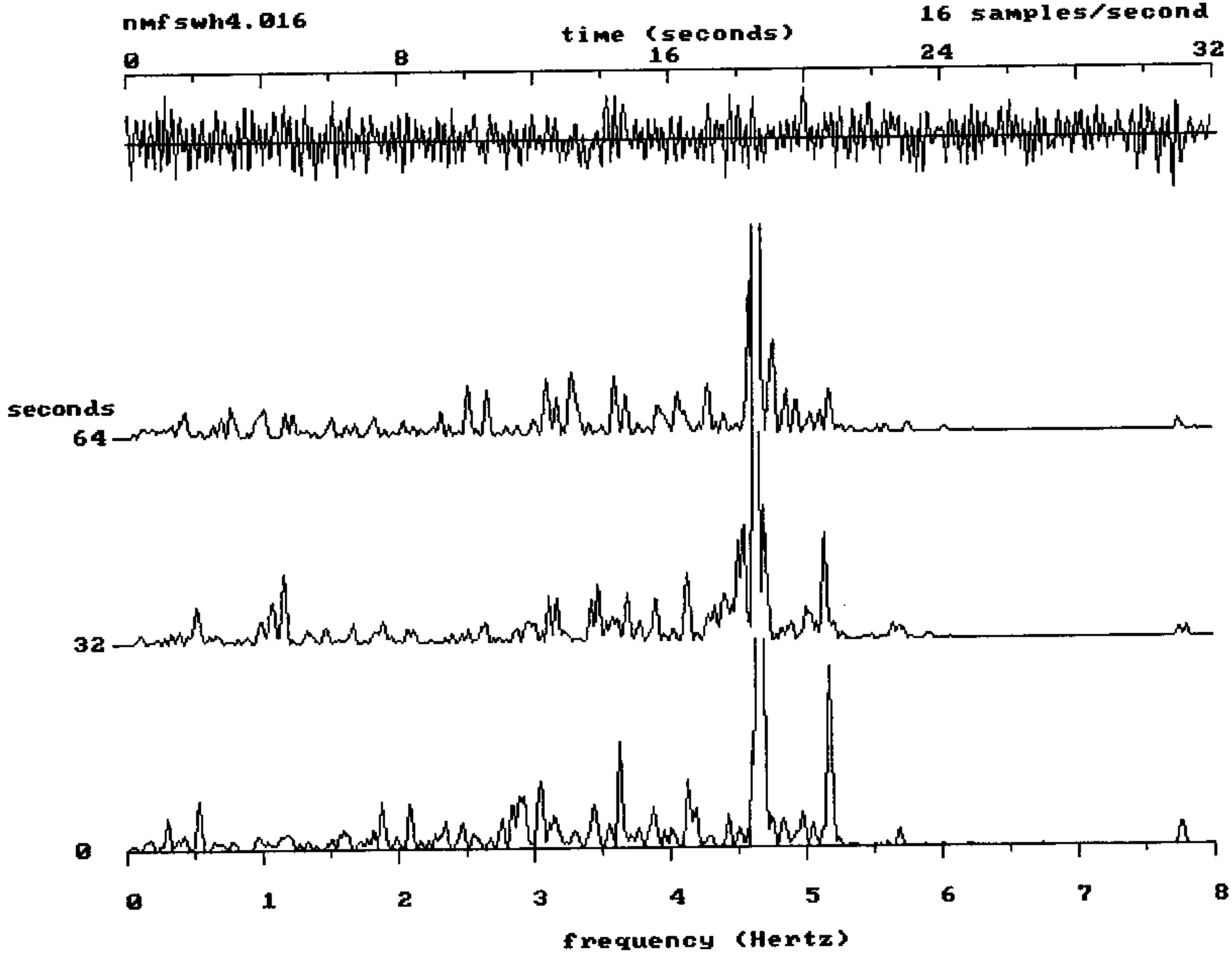
Sloop *Quicksilver* - August 4, 1981 - Stellwagen Bank, NW
lamn1.032
The humpback whales were vocalizing and tailslapping during this sequence of spectra. A stationary signal at 2.6 to 2.7 Hz is an indicator that sustained low frequency finbeats can be detected for tracking at sea.

Little Torch Key, Florida, Betty Brother's Dolphin Lagoon, April 18, 1990
suwa1.032
Suwa was a 28 year old male bottlenose loner dolphin living in a 200 foot oval lagoon. The first spectrum shows distributed energy to 6 Hz with a spike at 1.3 Hz. Spikes at .7, 1.6, 1.9, 2.3 and 3 Hz show finbeats.

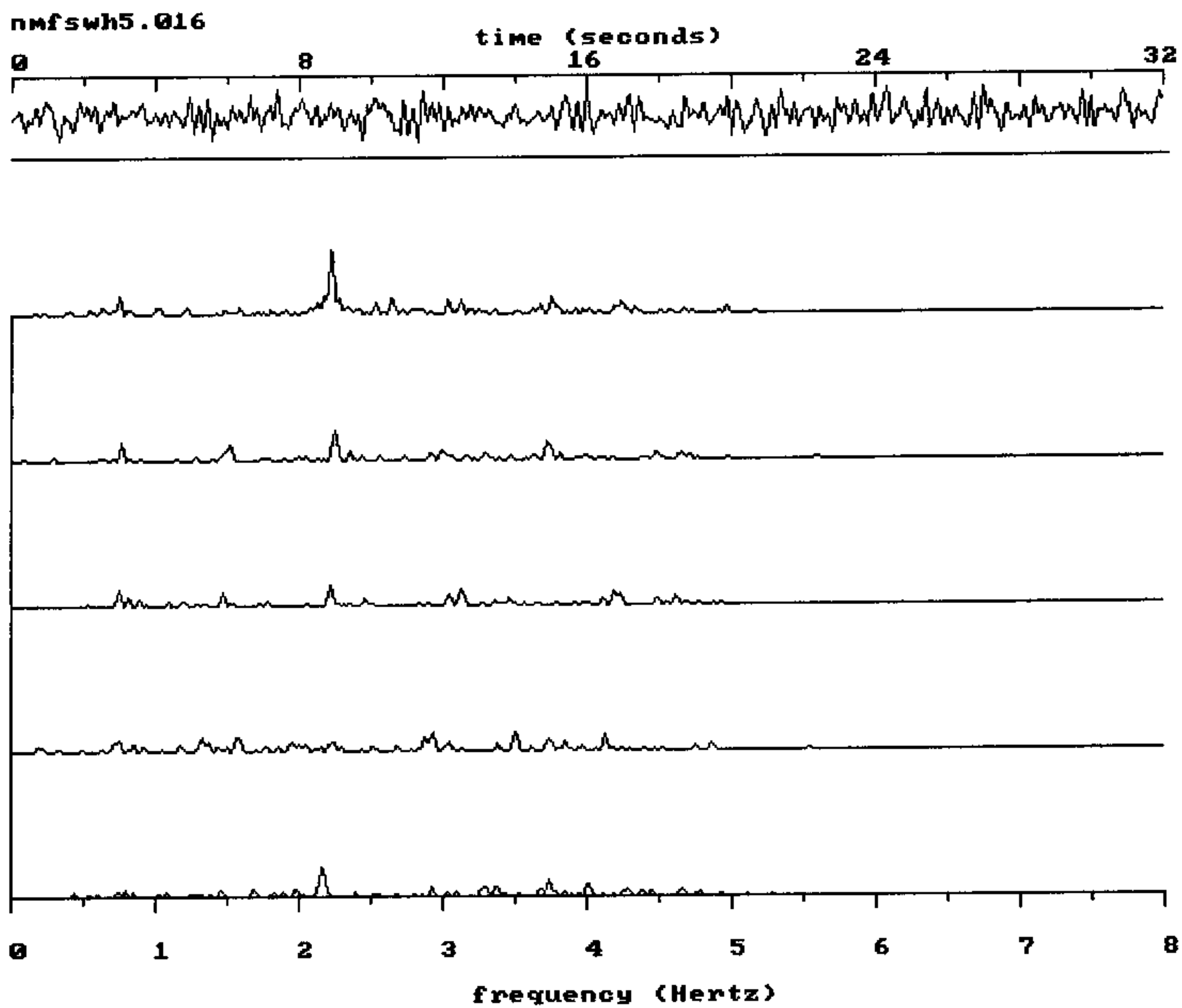
R/V Halos, Cape Cod Bay, April 19, 1984, Center for Coastal Studies, Provincetown
egl8.p16
This shows the ensonifications from a north atlantic right whale cow calf pair on an 8 KHz spectrum bandwidth The train of spikes on the left is isotropic ocean noise plus finbeats.

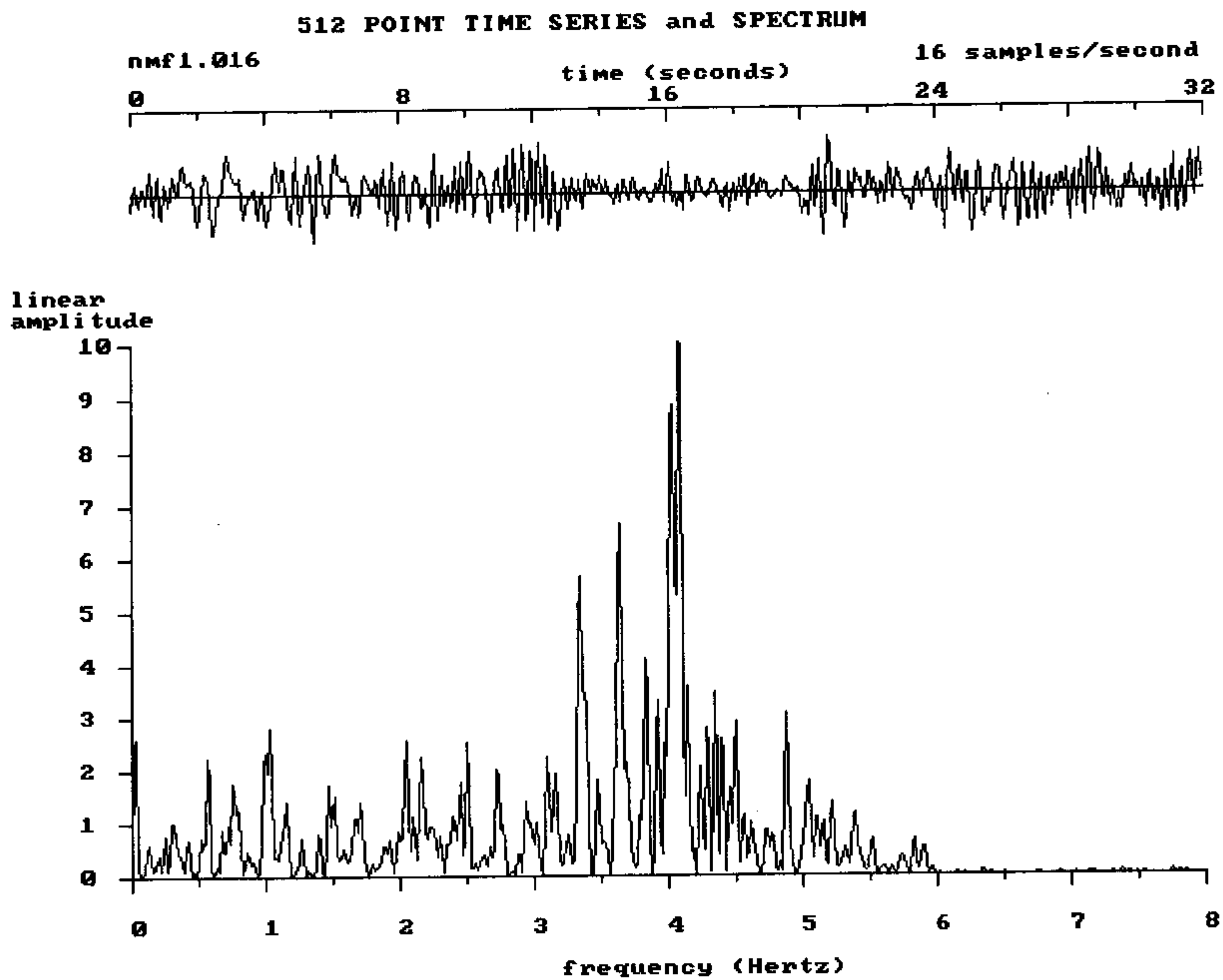
Tongue of the Ocean, Andros Island, Atlantic Undersea Testing and Evaluation Center,23April 1978
toto6.128
This recording of sperm whale click trains was made on a Sangamo 14 track recorder at 120 inches/second and transferred at 30 inches/second to a cassette at 1 7/8 inches per second. Discrete click repetition rates and mode excitations center on 150 Hz and extend from 176 to 256 Hz.

512 POINT TIME SERIES and SPECTRUM SEQUENCE



512 point time series and spectrum sequence

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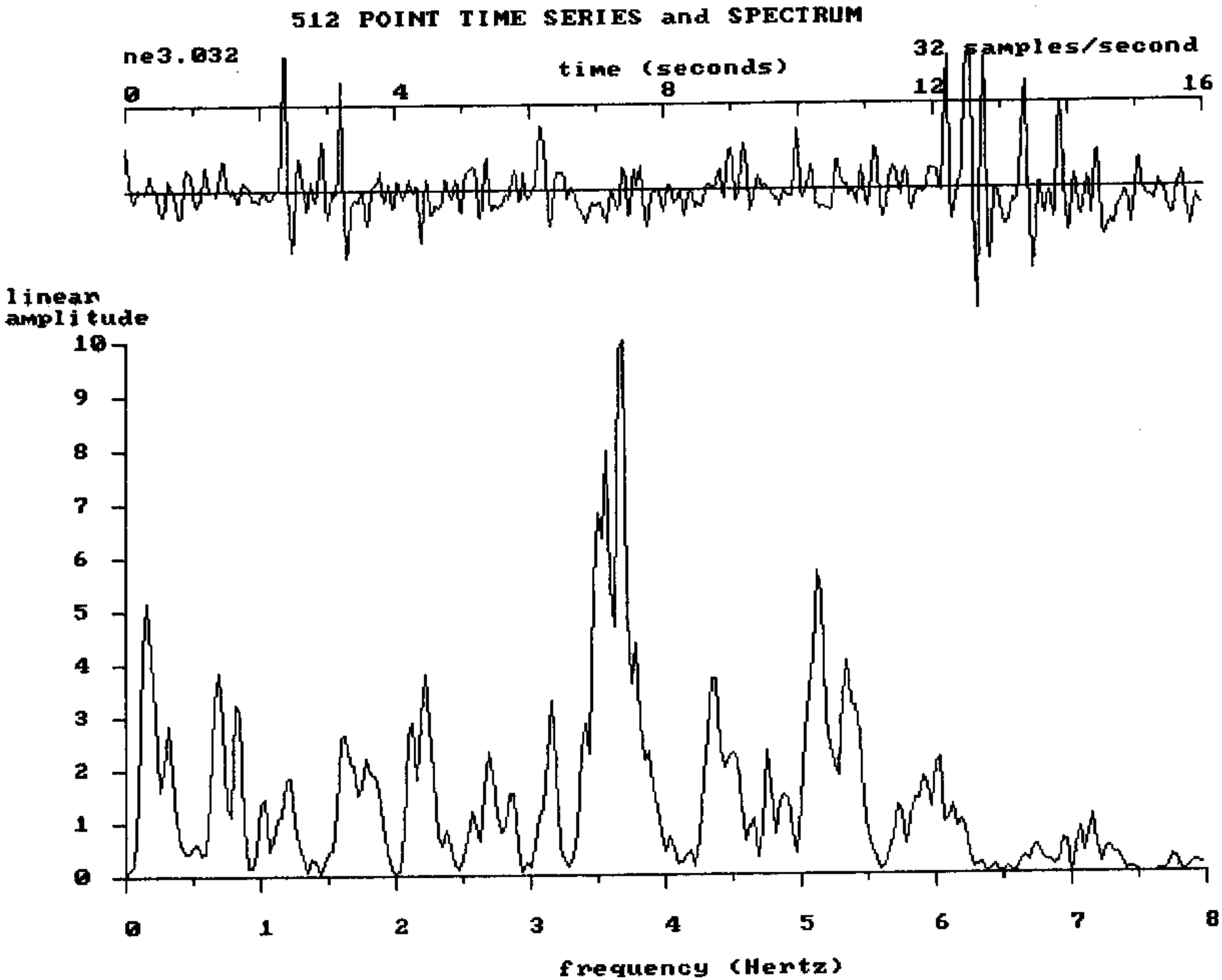
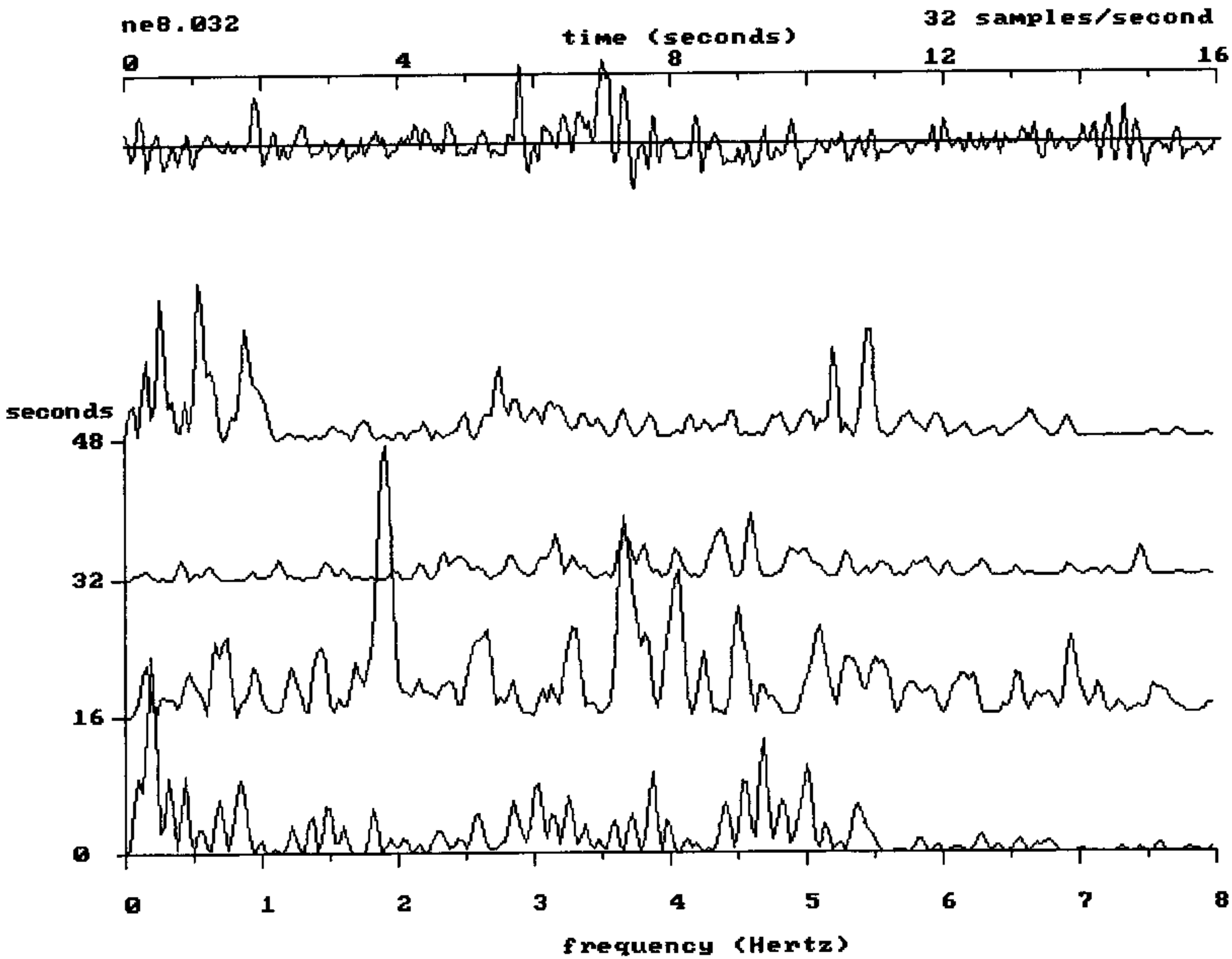
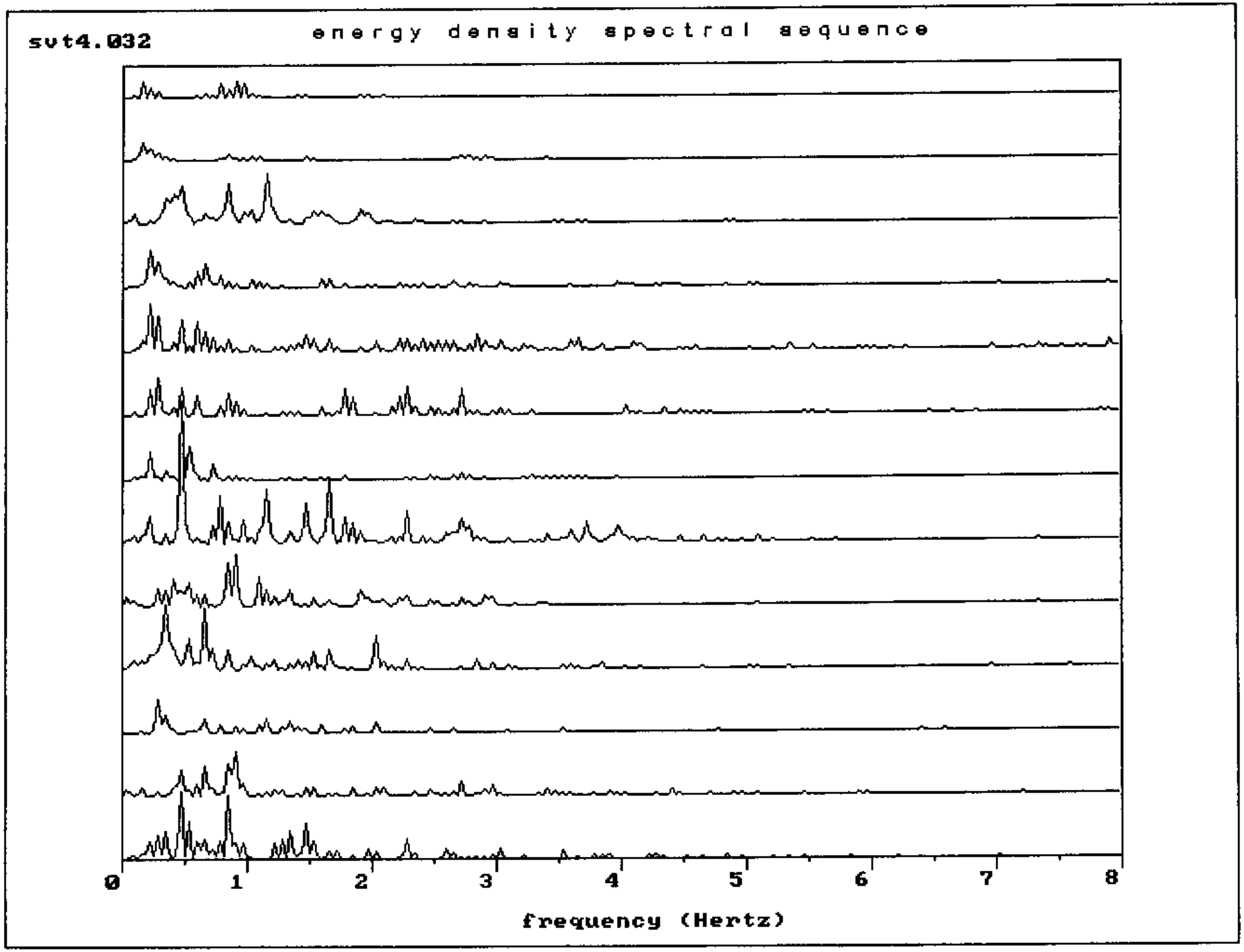
16 samples/second
time (seconds)
0
8
16
24
32
linear
amplitude
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
frequency (Hertz)


512 POINT TIME SERIES and SPECTRUM
ne3.032
32 samples/second
time (seconds)
0
4
8
12
16
linear amplitude
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
frequency (Hertz)

512 POINT TIME SERIES and SPECTRUM SEQUENCE

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energy density spectral sequence
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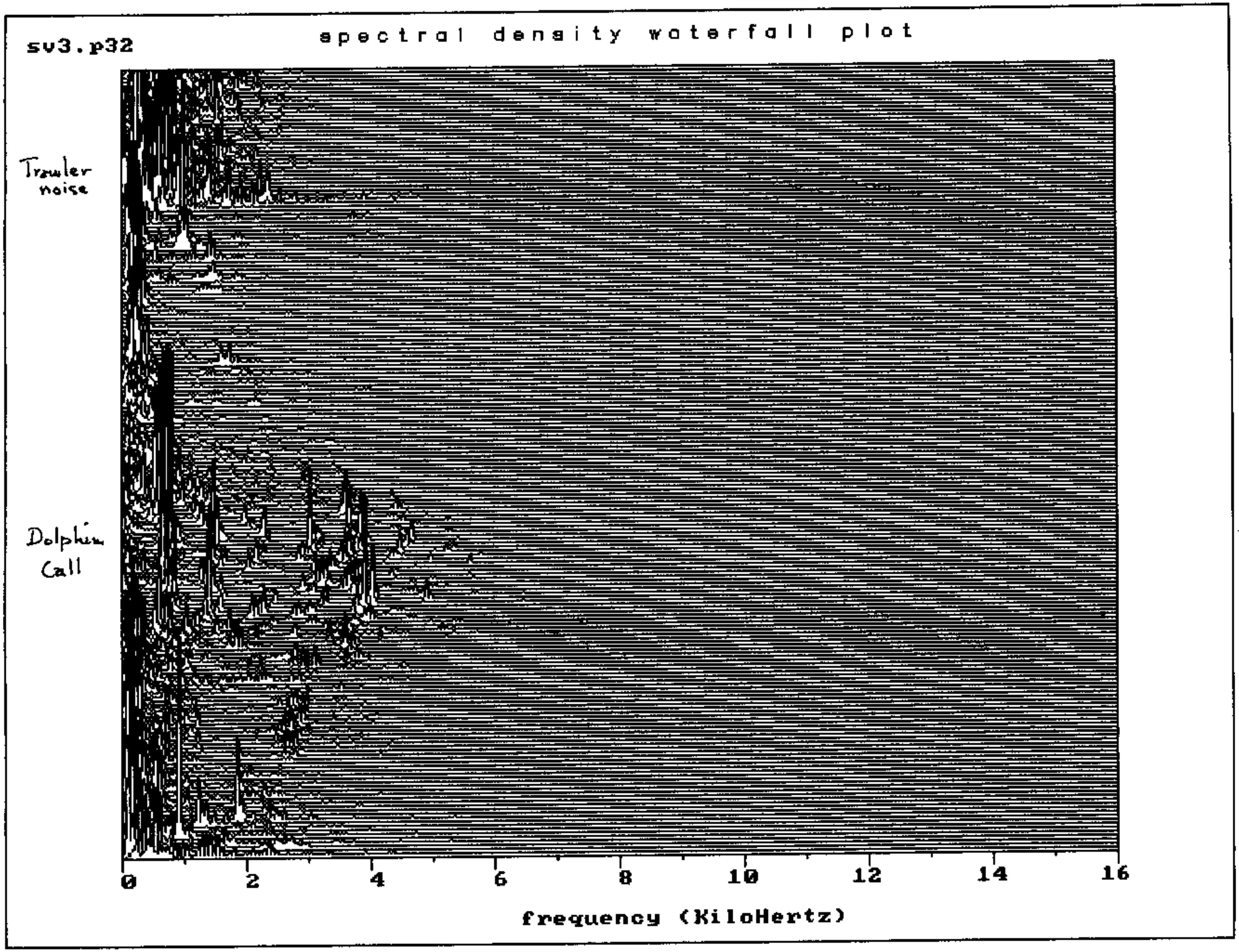
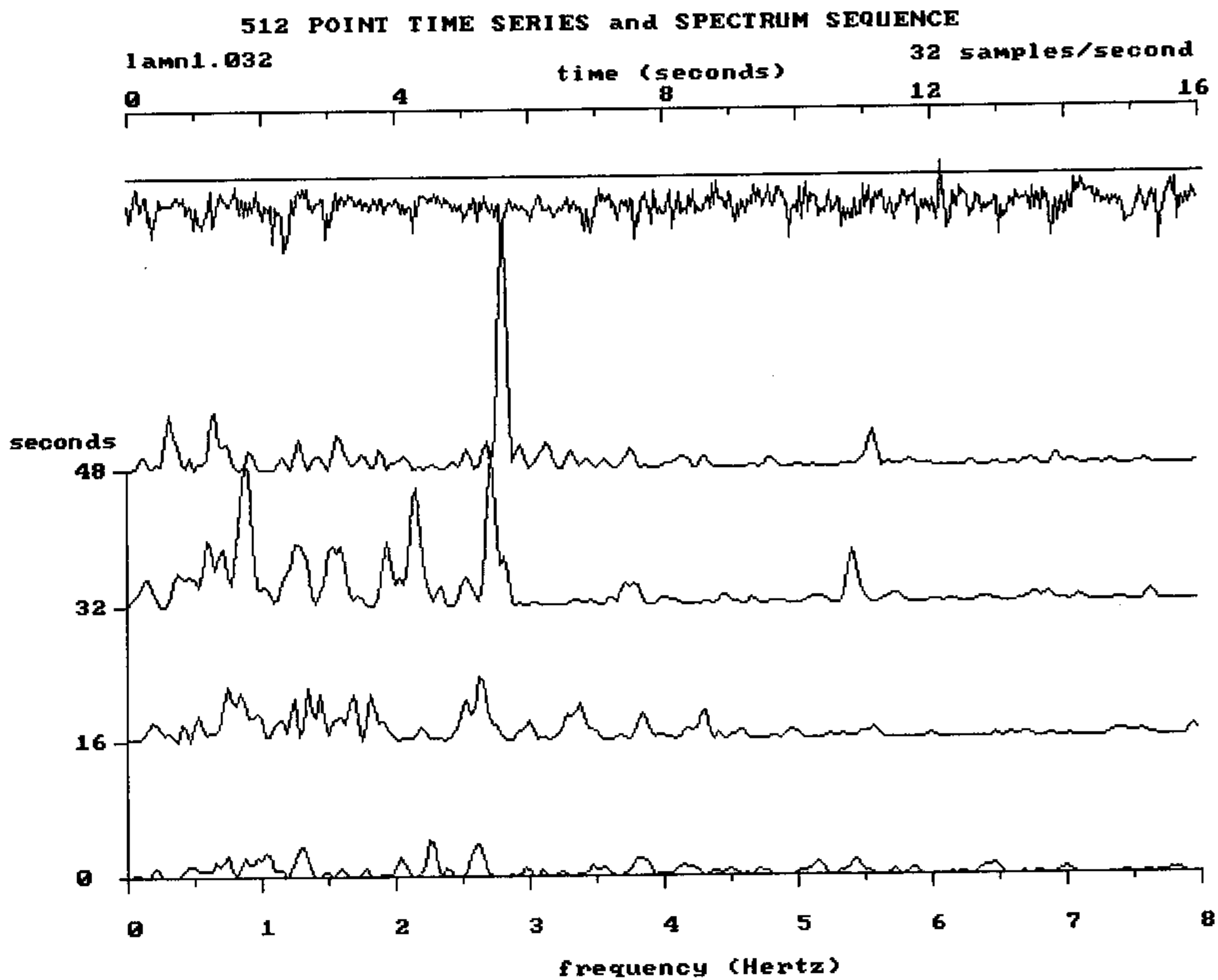
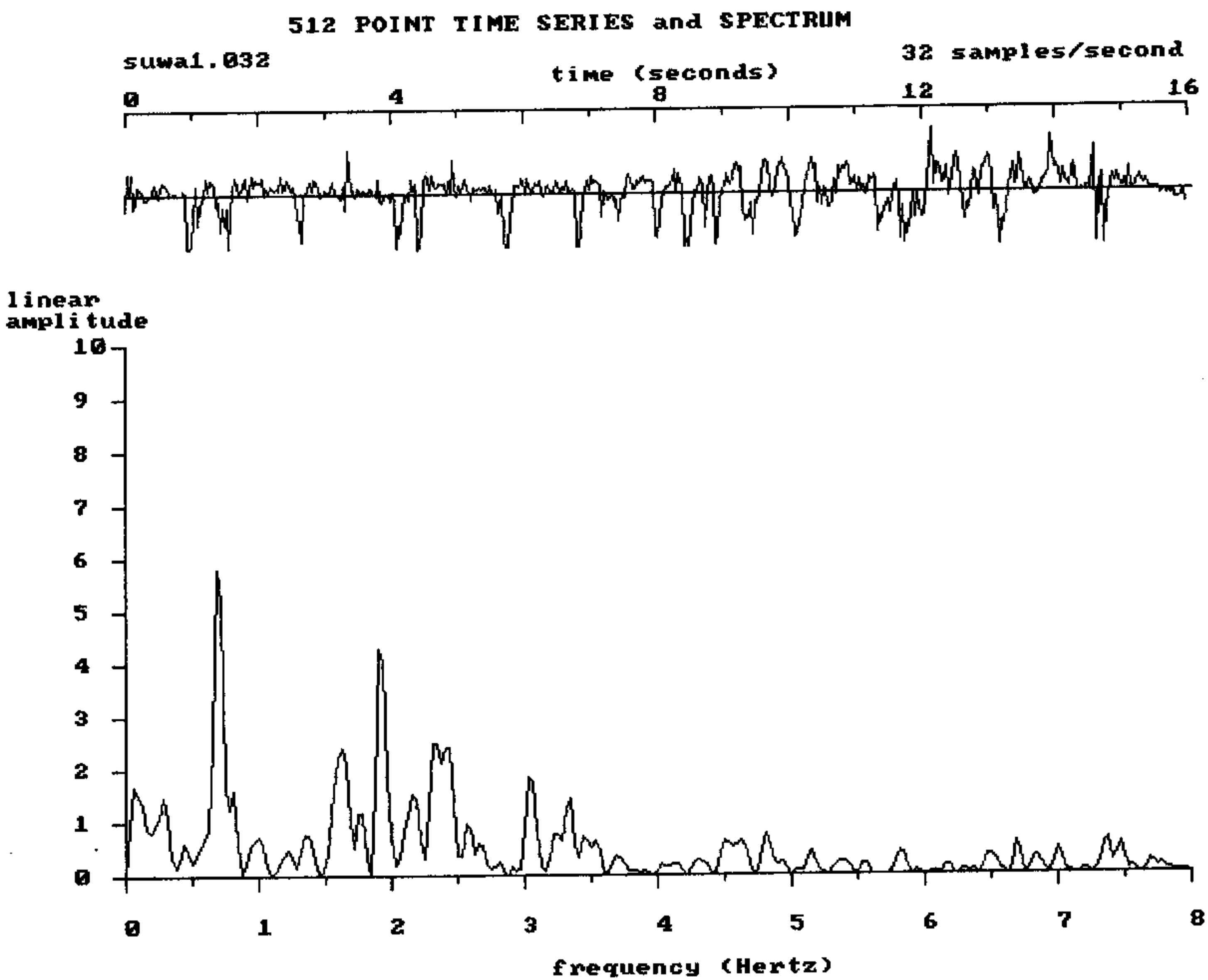
1
2
3
4
5
6
7
8
frequency (Hertz)


sv3.p32
spectral density waterfall plot
Trawler noise
Dolphin Call
0
2
4
6
8
10
12
14
16
frequency (KiloHertz)


512 POINT TIME SERIES and SPECTRUM SEQUENCE
lamn1.032
32 samples/second
time (seconds)
0
4
8
12
16
seconds
48
32
16
0
0
1
2
3
4
5
6
7
8
frequency (Hertz)



512 POINT TIME SERIES and SPECTRUM
suwa1.032
32 samples/second
time (seconds)
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4
8
12
16
linear amplitude
10
9
8
7
6
5
4
3
2
1
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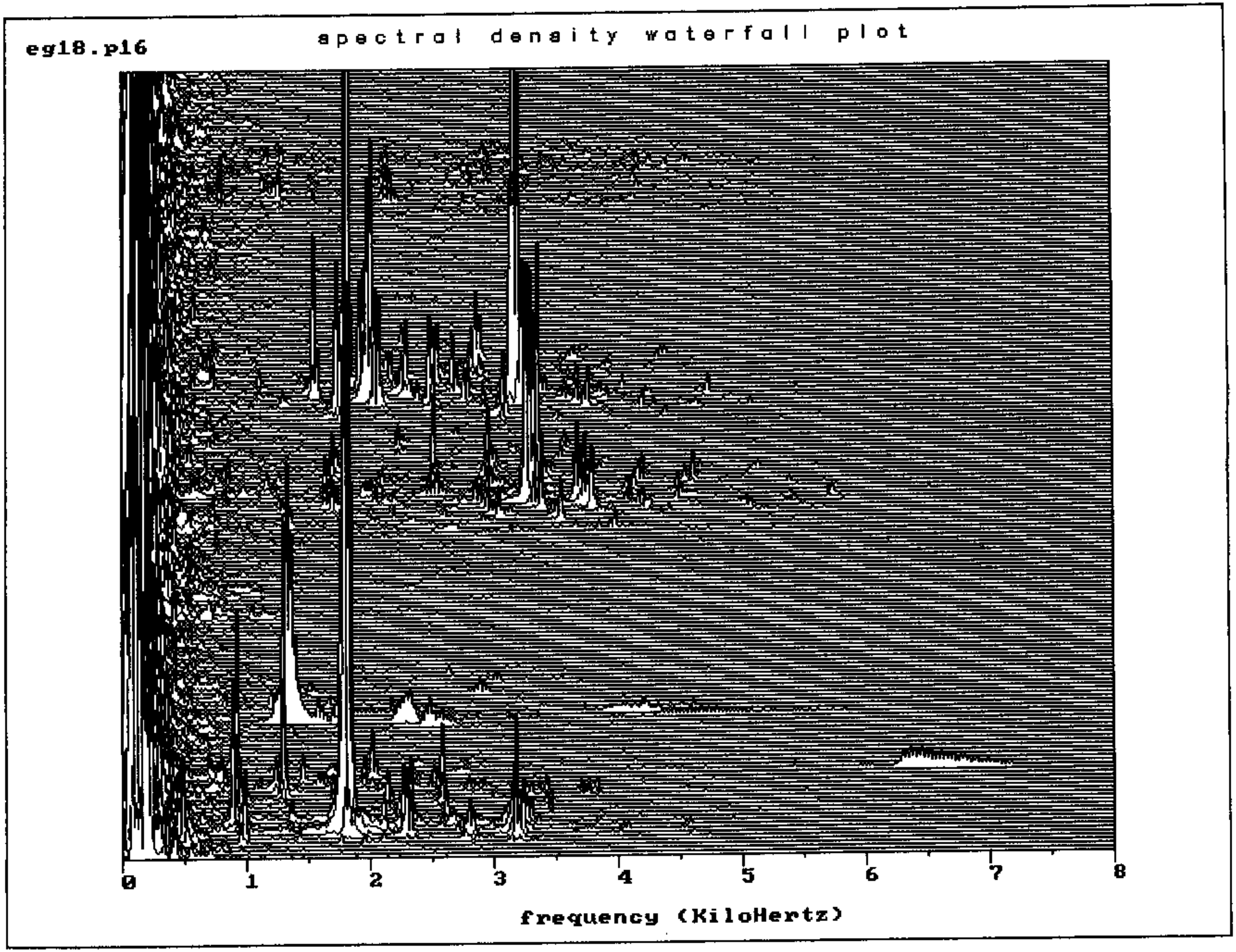
1
2
3
4
5
6
7
8
frequency (Hertz)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spectral density waterfall plot
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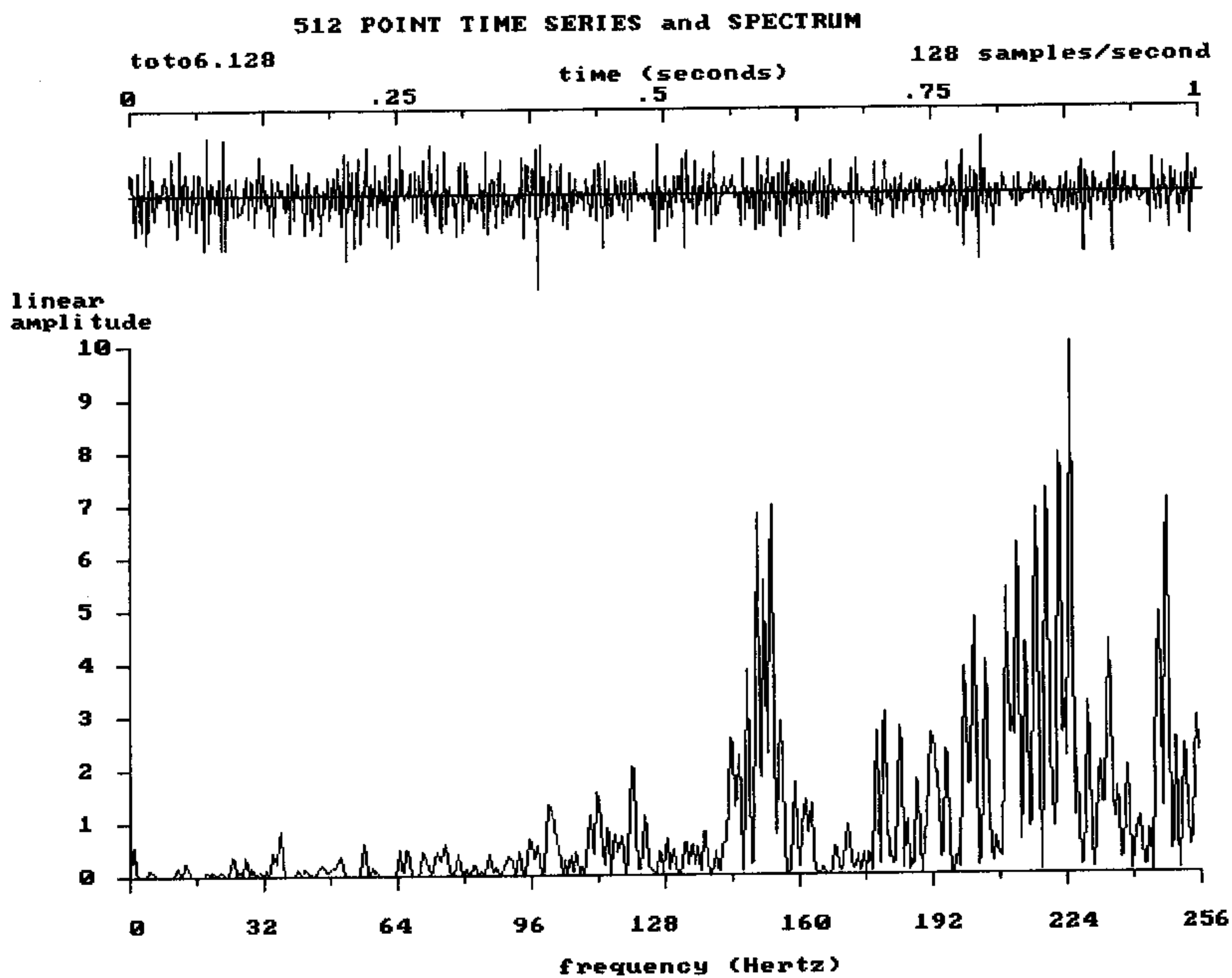
2
3
4
5
6
7
8
frequency (KiloHertz)


512 POINT TIME SERIES and SPECTRUM
toto6.128
128 samples/second
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.75
1
linear amplitude
10
9
8
7
6
5
4
3
2
1
0
0
32
64
96
128
160
192
224
256
frequency (Hertz)