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Pacific Northwest National Laboratory
Operated by Battelle for the
U.S. Department of Energy

Observations of the Behavior and Distribution of Fish in Relation to the Columbia River Navigation Channel and Channel Maintenance Activities

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Prepared for the
U.S. Army, Corps of Engineers – Portland District
under a Related Services Agreement with the
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Executive Summary

Beginning in 1995 and continuing through 1998, researchers from Pacific Northwest National Laboratory (PNNL), the U.S. Army Corps of Engineers (CE)' Engineering Research and Development (ERDC) facility, and AscI Corporation conducted a series of studies at Jones Beach reach on the lower Columbia River near river mile 45 to augment available information on the distribution and behavior of fish, particularly migrating juvenile salmonids, relative to the lower Columbia River navigation channel and channel maintenance structures and activities. All studies were conducted using nonintrusive means to avoid taking endangered species. The location and time of year were selected to coincide with past studies of salmonid smolt outmigration at Jones Beach conducted by the National Marine Fisheries Service.

This report summarizes the findings from these five studies, conducted for CE between 1995 and 1998. The findings were originally written in draft form and presented to CE in the years each study was performed. Two additional studies, prepared for others, are also provided here as appendixes.

- "Review of Smolt Migratory Behavior at Jones Beach and Feasibility Assessment of Using Hydroacoustic Methods for Smolt Behavior Monitoring" – This study, completed in 1995, included literature reviews of salmonid migratory behavior through the Jones Beach reach and salmonid response to turbidity plumes and sound fields generated by marine construction activities. The study also included observations of dredging operations to determine locations for sound field measurements and passive and active hydroacoustic measurements to determine if dredging activities generate sound in the sound spectrum used for hydroacoustic assessment.

- "The Behavior of Fish in the Vicinity of a Pile Dike in the Lower Columbia River" – This study, conducted in 1996, used hydroacoustic transducers positioned along a pile dike located at Jones Beach to observe day and nighttime fish behavior near shore, along the dike, and near the navigation channel.

- "Characterization of Underwater Sound Generated by Impact Pile Driving" – This study, conducted in 1996, used hydrophones to measure underwater sound from pile driving activities to determine if the duration, frequency, and pressure values associated with impact pile driving would be likely to stimulate a sustained avoidance response by salmonids.

- "Observations of the Behavior of Fish Relative to the Columbia River Navigation Channel and Channel Maintenance Activities in 1997" - This study, conducted in 1997, used mobile hydro acoustic surveys to monitor fish distribution across the river during the spring and summer juvenile salmon out-migration.

- "Observations of the Behavior of Fish Relative to the Columbia River Navigation Channel and Channel Maintenance Activities in 1998" - This study used mobile hydroacoustic surveys to monitor diel vertical and horizontal fish distribution in the river during the summer juvenile salmon outmigration.

- "The Characterization of Underwater Infrasound Generated by Vibratory Pile Driving within the Context of the Characteristics of Sound Known to Result in Avoidance Response by Juvenile Salmonid" – This study, conducted in 1996 for Oregon State University and included as Appendix A to this report, measured the sound field generated by vibratory pile driving during construction of a new pier at the Hatfield Marine Sciences Center, Newport, Oregon.

- "Turbidity Monitoring, Beach Nourishment, Miller Sands, July 20, 1994" – This field report was prepared by the Portland District Corps of Engineers and is included as Appendix B.

Based on these studies, the following overall conclusions can be made:

- Migrating juvenile salmonids respond to the presence of pile dikes.

- Salmonid response to pile dikes differs between day and night.

- During the day the majority of the fish appear to move past the offshore end of the dike.

- During the night there is a decrease in the numbers of salmonids passing the dike and an increase in the numbers of fish holding/milling within the region immediately downstream of the dike.

- The proportion of salmonids that pass through the dike versus those guided by the dike and passing offshore of the end of the dike could not be estimated from available data.

- No differences between day and night in the horizontal and vertical distribution of salmonids across the river cross-section were detected using mobile hydroacoustic sampling methods.

- The majority of salmonids detected across the river cross-section were within 7 meters of the bottom.

- The majority of detected salmonids were observed along the navigation channel margin – a habitat zone not identified in previous studies.

- Migrating salmonids responded to the presence of the dredge and dredge plume.
    - Fish orienting to the channel margin move inshore when encountering the dredge.
    - Most fish passing inshore moved offshore upon encountering the discharge plume.
    - Fish were observed to assume their prior distribution trends within a short time after encountering both the dredging activity and dredge plume.

- Underwater sounds generated by impact pile driving activities are within the frequency range to which juvenile salmonids have been observed to show an avoidance response.
    - The duration of sound at fish avoidance frequencies is very short, on the order of 0.025 seconds per impact, which is below the 5-second duration found necessary to elicit avoidance responses from juvenile salmonids in laboratory studies.

Contents

Figures

Tables

1.0 Introduction

In spite of several decades of research, there is still uncertainty about the details of juvenile salmon migratory behavior through the lower Columbia River. This is particularly true in reference to navigation channel structures and maintenance activities. Dredging to maintain the navigation channel and construction and maintenance of pile dikes are integral activities of navigation channel maintenance along the Columbia River. Specific concerns have been raised about how increased turbidity and underwater sounds from these activities might disrupt the normal migratory behavior of salmonids, some of which are listed under the Endangered Species Act, increasing their susceptibility to predation by other fish and birds.

Fisheries management agencies have expressed concern that navigation channel structures and maintenance activities conducted by the U.S. Army Corps of Engineers (CE) may impact migrating salmonid smolts in the Columbia River. Beginning in 1995 and continuing through 1998, researchers from Pacific Northwest National Laboratory (PNNL), the U.S. Army Corps of Engineers Engineering Research and Development (ERDC) facility, and AscI Corporation conducted a series of studies at Jones Beach reach in the lower Columbia River near river mile 45, funded by CE, to augment available information about the distribution and behavior of fish, particularly migrating juvenile salmonids, relative to the lower Columbia River navigation channel and channel maintenance structures (pile dikes) and activities (dredging and pile driving). These studies are summarized in this report.

The only previous long-term, species-specific studies of juvenile salmonid migratory behavior in the Columbia River were conducted by the National Marine Fisheries Service during two time periods, 1966-1972 and 1977-1983, at Jones Beach reach located at the upstream extent of the Columbia River estuary at river mile 45 (kilometer 75). Those studies used physical sampling methods – by beach seine, purse seine, and tow net – to determine fish distribution patterns (Dawley et al. 1986).

The studies presented in this report were conducted between 1995 and 1998 and were originally written in draft form and presented to CE in the years each study was performed. The location and time of year for the studies was selected to coincide with the studies conducted in 1966-1972 and 1977-1983. The studies reported here looked at migrating juvenile salmonids. Nonintrusive means were used to avoid taking species listed under the Endangered Species Act.

This report describes five studies conducted for CE. Two additional studies, conducted for others, are provided in appendixes.

- Chapter 2 presents “Review of Smolt Migratory Behavior at Jones Beach and Feasibility Assessment of Using Hydroacoustic Methods for Smolt Behavior Monitoring,” which describes a literature review of salmonid response to marine construction activity and an assessment conducted in 1995 of the feasibility of using hydroacoustic measurements taken during dredging operations.

- Chapter 3 is “The Behavior of Fish in the Vicinity of a Pile Dike in the Lower Columbia River,” a study conducted in August 1996 that used hydroacoustic transducers positioned along a pile dike located at Jones Beach to observe fish behavior around the dike.

- Chapter 4 is "Characterization of Underwater Sound Generated by Impact Pile Driving," a study that recorded sound field measurements during impact driving of 16 piles in a pile dike near Altona, Washington, in October and November 1996.

- Chapter 5 is "Observations of the Behavior of Fish Relative to the Columbia River Navigation Channel and Channel Maintenance Activities," a study conducted in 1997 that used mobile hydroacoustic surveys to monitor fish distribution across the river.

- Chapter 6 is "Observations of the Behavior of Fish Relative to the Columbia River Navigation Channel and Channel Maintenance Activities," a study using mobile hydroacoustic surveys to monitor vertical and horizontal fish distribution in the river at daytime, evening, and nighttime.

- Chapter 7 is references.

- Appendix A is "The Characterization of Underwater Infrasound Generated by Vibratory Pile Driving within the Context of the Characteristics of Sound Known to Result in Avoidance Response by Juvenile Salmonid," a study conducted in 1996 for Oregon State University to measure the sound field generated by vibratory pile driving during construction of a new pier.

- Appendix B is the field report "Turbidity Monitoring, Beach Nourishment, Miller Sands, July 20, 1994," which was prepared by the Portland District Corps of Engineers and is included like Appendix A because of its relevance to the topic.

2.0 Review of Smolt Migratory Behavior at Jones Beach and Feasibility Assessment of Using Hydroacoustic Methods for Smolt Behavior Monitoring[a]

Fisheries management agencies have expressed concern that dredging activities conducted by the U.S. Army Corps of Engineers may impact salmonid smolts. For example, nearshore deposition of dredge materials could result in elevated turbidity and negatively influence the behavior of juvenile salmonids that utilize nearshore areas during their downstream migration. Another potential stimulus of concern is sound. Recent research has shown that juvenile Atlantic and Pacific salmonids can hear sound and do show an avoidance response to the hydrodynamic component of the near field of volume displacement infrasound sources (Hawkins and Johnstone 1978; Knudsen et al. 1992, 1994, 1997). Other species of fish have also been shown to respond to sound stimuli, with a large variation in sensitivity between species (Taft et al. 1995). As in the case of turbidity, the concern is that the response of migrants to sound will disrupt their normal behavior and, through one means or another, reduce their chances of survival.

To address these concerns, a reconnaissance-level survey of a dredging operation underway at Jones Beach in the lower Columbia River was conducted on September 5-6, 1995. The overall objectives of the study were to 1) conduct a limited literature review to determine the migratory timing and other aspects of the behavior of salmonid smolt passing through the Jones Beach reach; 2) conduct a limited literature review of juvenile salmonid response to turbidity plumes and sound fields generated by marine construction activities with emphasis on dredging; 3) observe dredging operations both from the shore and from the dredge to determine locations for sound field measurements and for hydroacoustic observations of fish behavior; and 4) perform passive and active hydroacoustic measurements at Jones Beach at 120 and 420 kilohertz (kHz) during dredging operations to determine whether dredging activities generate sound in the portion of the sound spectrum normally used for hydroacoustic assessment.

The hydroacoustic measurements of the dredging operation were conducted at Jones Beach, which is located 75 kilometers (km) from the mouth of the Columbia River at the upper end of the Columbia River estuary, approximately 50 km above the normal upper limit of saltwater intrusion. Water flow reversal occurs during flood tides. At Jones Beach the river is approximately 1.6 km wide with a sloped sandy beach and sandy channel. The U.S. Army Corps of Engineers conducts dredging at this site to maintain a 40-foot [ft]-deep by 600-ft-wide navigation channel. Dredged material is pumped to shore through a pipeline and deposited along the shorelines in designated areas. Figure 2.1 shows the bathymetry of the Jones Beach reach; the channel can be seen, along with the location of navigation buoys within the reach.

2.1 Literature Review

In 1995 we also conducted a literature review of salmonid response to sound fields and salmonid migration behavior in the Jones Beach area.

(a) This study was conducted by T.J. Carlson, R.L. Johnson, and R.P. Mueller while the senior author was with the U.S. Army Corps of Engineers Waterway Experiment Station, at Stevenson, Washington, in the fall of 1995.

2.1.1 Migratory Behavior of Juvenile Salmon through the Jones Beach Reach

From 1966 through 1972 and then from 1977 through 1983, the National Marine Fisheries Service (NMFS) sampled juvenile salmon and steelhead migrating past Jones Beach. Juvenile migrants were sampled with beach and purse seines and tow nets. The sampling sites, tools, and methods are reviewed in Sims and Johnsen (1974), which describes the beach seine in more detail. The report by Dawley et al. 1986 is the best resource available for information about the behavior of salmonid juveniles passing through the Jones Beach reach. The information given below is from this source.

2.1.1.1 Fall Chinook Salmon, 1966-1972

Beach seine sampling, which was conducted out to the 10-foot (≈ 3 m) contour, was used to capture 98% of the juvenile fall chinook taken at Jones Beach. These juvenile fish were consistently found concentrated in shallow near-shore areas throughout the estuary. Fall chinook salmon were found to be approximately 15 times more abundant in near-shore areas at Jones Beach than in adjacent offshore deeper channel regions. The distribution of fall chinook contrasted with that of yearling chinook, coho, and steelhead, which were most abundant in the offshore channel areas.

Sampling with a tow net, which could be set to sample at various depths, showed that when in deep water, the majority (95%) of juvenile fall chinook are found in the upper 3 m (≈ 10 ft) of the water column.

Movement of juvenile fall chinook through the Jones Beach reach peaked during two daytime periods, one in the morning between 0800 and 1100 hours and another smaller peak in the evening between 1800 and 2000 hours. Marked fish released at night tended to remain in the area of release much longer than those released during the day. This information, in addition to the observations of the time of occurrence of peak passage, led the researchers to conclude that juvenile fall chinook are most actively migrating during daylight periods.

More than 80% of juvenile fall chinook were observed to pass between April 28 and September 2. Peaks in abundance typically occur in May and early June and in late July or early August. The later peak is typically the highest. Although variations between years can be significant, in general, migration remains heavy through mid August declining to low levels by September and continuing to decline through the fall.

The rate of downstream movement of juvenile fall chinook was estimated to vary between 5 to 36 km per day with larger fish generally migrating faster than smaller fish and with most juveniles migrating rapidly through the estuary. Tidal conditions and direction of flow did not seem to influence the diel movements of juvenile fall chinook.

2.1.1.2 Coho Salmon, 1966-1971

When both beach and purse seining were conducted, juvenile coho were found to be more abundant in the offshore channel area. Juvenile coho were most abundant from mid-April through early June, then their abundance declined to low levels. In all years, peak catches of juvenile coho occurred between May 5-16. Maximum catches of coho were made at midday between 0600 and 2000 hours. Despite hatchery release dates and environmental variability the time of peak abundance was the same. The average migratory travel rate of coho was estimated to be between 3 and 26 km per day.

2.1.1.3 Salmonids, General 1977-1983

Both subyearling and yearling chinook were taken. Subyearlings were primarily fall and summer races, while the yearling chinook were primarily spring fish.

Peak abundance of yearling and subyearling chinook, coho, and steelhead occurred during May and early June. Yearling fish abundance declined rapidly through June and was at low levels by early July. The peak in catches of yearling chinook, coho, and steelhead occurred in late May. Catches of subyearlings remained high through July and August, with peak catches within this time correlated with major hatchery releases and river flow.

Migratory rates averaged between 7 and 36 km per day. Observations of marked fish determined that there is little migratory delay by fish in the estuary.

The largest catches occurred between sunrise and early afternoon in near shore areas for subyearling chinook, between sunrise and early afternoon in mid-river for yearling chinook, from mid-morning to later afternoon near shore and early morning and early afternoon in mid-river for coho. Peak catches of steelhead and sockeye both occurred in mid river, between noon to early evening for steelhead and during daylight for sockeye. The first catches in early morning were often the highest, apparently because of the accumulation of fish during the night.

All salmonids showed decreased downstream movement during darkness. No relationship between migratory timing and tidal cycle was found.

Although there were exceptions on occasion, in general yearling salmon were caught in mid-river areas by purse seines and most subyearlings were captured near shore with beach seines. The size distributions in the near shore catches compared with those off shore provided additional evidence that larger juveniles are more likely to be caught in mid-river and smaller juveniles near shore. One exception was that early in the year through mid-April, yearling chinook and coho salmon were captured near shore; otherwise, the trend was for larger juveniles, even larger subyearling chinook, to be caught offshore.

2.1.1.4 Other Observations of Juvenile Salmonid Migratory Behavior

The observations of peak passage of juvenile salmonids through the Jones Beach reach during daytime contrasts with the observed behavior of these same fish during passage through upriver dams. Giorgi and Stevenson (1995) in a recent review of studies of juvenile migrant behavior at lower river dams found that the majority of juveniles pass during the approximately 8-hour period between dusk and dawn. This is exactly opposite the migration pattern found at Jones Beach by Dawley et al. (1986). However, other studies of the behavior of salmonids in tributaries indicate that juvenile salmonids remain inactive at night (Don Chapman Consultants 1989). Apparently the tendency of juvenile salmonids migrating past Jones Beach to be most active during the day is more similar to their behavior patterns in more natural settings than it is to their behavior at dams.

2.1.2 The Characteristics of Sound Fields Known to Affect Juvenile Salmonid Behavior

Dredges, ships, other human activities, and natural events are known to be sources for sound at frequencies shown to be heard by many species of fish (Urick 1983; Greene and Moore 1995). While it has been shown that dredging is a source of continuous low-frequency sound with energy at the infrasound frequencies known to stimulate salmonid avoidance, it is not known if the amount of near-field energy in the form of large water particle motion at infrasound frequencies is sufficient to cause avoidance. In other words, while sound energy may be present at the correct frequencies, it may not be present in the form that stimulates salmonid avoidance. The reason for this uncertainty is that, to date, measurements of sound fields resulting from marine construction activities have been made using pressure-sensitive devices at locations well outside of the region near the sound sources where large particle motions, now known to be the stimulus for salmonid avoidance responses, occur (Feist 1992; Greene and Moore 1995; Harris 1964; Kalmijn 1988).

Considerable progress has been made in the last 10 years in understanding what salmonids, and other fish, can hear and their behavioral response to what they hear (Carlson 1994; Popper and Carlson 1998). The basic audiogram for salmonids was determined in 1978 (Hawkins and Johnstone 1978) and recast by Kalmijn (1988) to take into consideration the physical stimulus - water particle acceleration - to which the salmonid inner ear and lateral line respond. Kalmijn's analysis showed that salmonid hearing is most sensitive below approximately 150 hertz (Hz), retaining maximum sensitivity through the infrasound region.

Repeatable avoidance responses by Atlantic and Pacific salmonids and steelhead, and many other species, have been obtained under both laboratory and field conditions (Knudsen et al. 1992, 1994; Taft et al. 1994; Mueller et al. 1998; Ploskey et al. 2000). The effective stimulus has been identified to be the local flow component of infrasound in the range of 5 to 30 Hz where water particle acceleration is greater than 0.01 milliseconds $(ms)^{-2}$. The effective stimulus for avoidance response is only found in the near field of sources capable of generating a local flow field with water particle acceleration greater than the above threshold. The effective stimulus for avoidance response by salmonids does not exist in the far field of any source nor in the near field of sources that do not have significant displacement amplitudes of their active element (i.e., greater than 0.01 meter [m]). While there is still some uncertainty about the frequency range below 100 Hz within which salmonids will respond, there is no uncertainty that salmonids respond primarily to water particle motion and not pressure.

An avoidance response resulting in exposed fish actively swimming away from the infrasound source typically requires several seconds of exposure. Laboratory and field studies that have demonstrated a consistent avoidance response from salmonids and other fish use infrasound signals that are 4 to 6 seconds in duration. These studies have also shown that exposed fish habituate with continued exposure but recover from habituation within short periods of no exposure (Knudsen et al. 1992, 1994; Taft et al. 1994; Mueller et al. 1998).

It has been shown that salmonids do not respond to the pressure component of sound fields. Research conducted in Europe (Knudsen et al. 1992, 1994), and recently in the United States (Knudsen et al. 1997; Taft et al.1995), has shown a strong avoidance response by juvenile salmonids to the large hydrodynamic displacements in the near field of volume displacement sources with high energy output at frequencies around 10 Hz (10 cycles per second). The nature of these sources and this portion of the sound field is such that sufficiently high water particle acceleration, the effective avoidance stimulus for salmonids, is only present at short distances from sources (2 to 3 m, 7 to 10 ft). The larger the volume displaced by the source, and the larger the peak-to-peak amplitude of the active element of the source as it cycles, the greater the effective range of the source. Volume displacement sources used in research have amplitudes of displacement on the order of 1.5 to 2.5 inches (roughly 4 to 6 cm). These sources generate fields causing avoidance responses by juvenile salmonids that extend out from the source on the order of 10 feet (≈ 3 m).

Pressure transducers, the instruments typically used to measure sound fields, cannot be used to measure that portion of a sound source near field that juvenile salmon avoid. Accelerometers or other measurement technologies, such as particle image velocimetry, are required to measure the amplitude, frequency, and directionality of the hydrodynamic portion of the near field. While some measurements exist of the far field generated by dredging and other marine construction activities, few measurements have been made in the near field at infrasound frequencies, Of those made in the near field, none have been made of the hydrodynamic component of the generated field.

It is interesting that recently the international fisheries scientific community prepared a research report that analyzed the underwater noise generated by research vessels and made recommendations for the design and operation of research vessels to limit vessel noise (Mitson 1995). This research was undertaken in response to well-documented concerns by fishery scientists that noise generated by their research vessels was affecting the behavior of the fish they were assessing, thereby biasing their assessments of fish stocks. While this report summarizes a great deal of information about the underwater noise generated by vessels, it is limited to the types of far field acoustic pressure data typically acquired over the last 40 years and does not contain information relevant to potential salmonid avoidance of dredging operations. The significance of the report within the context of this study is the recognition by fishery scientists worldwide of the behavioral response by fish to sound generated by vessels.

It is not possible, given the lack of information about the near field infrasound particle displacements in the vicinity of vessels, dredges, and other marine construction equipment, to address the impacts of sound from such operations is likely to have on juvenile salmon migratory behavior at marine construction and dredging sites in general, or at Jones Beach in particular. Obtaining such basic measurements should be a high priority and should precede or be part of any study to observe fish behavior. The reason for this recommendation is that the locations of volume displacement sources of sound and maps of the fields generated by them will be required for the design of studies to assess the impact of these sources on the migratory behavior of salmonids. Without such information, considerable time could be spent observing fish behavior in locations void of adequate sound stimulus.

Two types of measurements will assist with the assessment of the sound fields generated by marine construction activities. Volume displacement sources should be easily detected since fairly large displacements of water are required to generate the hydrodynamic component of the near field required for salmonid avoidance. This means that measurements can be made on those parts of equipment in direct contact with water. Displacements (vibrations) on the order of an inch (2.54 cm) at infrasound frequencies are required to generate a stimulus capable of causing salmonid avoidance responses with effective ranges extending any distance from the point of water contact. Therefore, measurements should be made at dredging sites by placing accelerometers or other suitable measurement devices on the various types of equipment in contact with water to measure the frequency and magnitude of displacement of any vibratory motion. These measurements should be followed by measurements in water to characterize both the near and far field generated by these sources. While a machine part might be vibrating at infrasound frequencies, it may be inefficient, for any of several reasons, in transferring energy into the water. In order to detect and characterize stimulus fields potentially causing avoidance responses by salmonids, sound field measurements should focus on determining the frequency content and magnitude of the hydrodynamic component of the near field of suspected sources vibrating at infrasound frequencies.

2.2 Observations of Dredging Activity

To maintain a 40-foot-deep navigation channel, CE routinely dredges to remove deposited material. Dredging is conducted 24 hours a day, late spring through early fall. Deposited material is cut from the channel, pumped into a pipeline connected to the dredge by a section of flexible pipe, carried to the shore, and deposited. Dredge disposal sites are located on both the Oregon and Washington sides of the river. The disposal site used on any particular day depends on the location of the dredge and which disposal site is closer.

The pipeline that carries the dredge spoils to the shore is approximately 2 feet in diameter. The pipeline is held above water over most of the distance from the dredge to the shore by a series of large cylindrical tanks, approximately 25 feet long and 4 feet in diameter, which are spaced approximately every 25 feet along the pipeline. The long axes of the pipeline and the individual tanks are orthogonal. Barges, approximately 20 feet wide by 60 feet long, are positioned at sharp (i.e., 90°) bends in the pipeline. On September 5-6, 1995, a portion of the pipeline near shore was underwater to permit access by vessels to the near shore area. Discussions with the dredge operators indicated that, for most installations, a section of the pipeline is submerged to permit vessel access to the navigation channel or other portions of the river and its tributaries. The configuration of the pipeline can change on a daily basis as the cutting head of the dredge is moved from location to location and the length and configuration of the pipeline are changed to accommodate new locations.

In addition to the marine traffic using the navigation channel, which includes large ocean-going transports, barge tows, and recreational vessels of varying size, there is considerable activity by large specialized work boats in the immediate vicinity of the dredging operations when the pipeline is being repaired or repositioned. These vessels are used to push or pull sections of pipe into position, to replace anchors, and for a multitude of other tasks required to work with the pipeline. A jet-powered crew boat makes trips to and from shore facilities frequently. Typically, the periods of highest activity by the dredging crew occur during the day when the pipeline is repositioned, although dredging usually takes place 24 hours a day.

The high level of activity around the dredge, which include use of the dredge as a dock by the work boats and crew boat, will prevent using the dredge as a base for deployment of hydroacoustic instruments. The extensive wakes of the work boats and the docking activity by the crew boat and the work boats make deployment and maintenance of a hydroacoustic system difficult and create an underwater environment not conducive to hydroacoustic observation of migrating juveniles. While there would be periods when conditions at the dredge might be favorable for hydroacoustic observations, it would be difficult to maintain a sampling schedule. Unfortunately, the period when work activity would be lowest, during the night, is also the time when the migratory behavior of the smolt is at its lowest, so the value of behavioral observations at that time is also low.

Under normal operations, the pipeline and its supporting tanks were not observed to be vibrating to any extent. However, the period of observation was short, approximately 4 hours, and may not be indicative of behavior at other times. A lack of noticeable vibration is important because significant vibration (oscillatory movement on the order of inches) can generate the high-intensity particle motion fields found in the near fields of volume infrasound sources that salmonids have been shown to avoid (Knudsen et al. 1992, 1994, 1997).

No broad band sound field measurements were made; nor did we attempt to determine the source of sounds detected at the measured frequencies (120 Hz and 420 Hz) during the September survey. It is clear from observations of dredging activity made during the survey that sound field measurements will need to be made during those periods of pipeline maintenance activity, in addition to other times, to adequately characterize the sound fields present due to dredging operations. In addition, it is likely that the large vessels that periodically pass through the reach contribute significant amounts of sound and hydrodynamic energy, perhaps as much as or more than dredging operations. The sound generated by large ocean-going vessels has been measured and is known to be significant, perhaps high enough to affect fish behavior (Mitson 1995).

2.3 Hydroacoustic Measuring at Dredging Site

Passive and active hydroacoustic measuring were performed at Jones Beach at 120 and 420 kilohertz (kHz) during dredging operations to determine whether dredging activities generate sound in the portion of the sound spectrum normally used for hydroacoustic assessment.

2.3.1 Methods

2.3.1.1 Methods for Background Sound Measurements

Calibrated hydroacoustic systems operating at 120 kHz (Precision Acoustic Systems Model 103) and 420 kHz (BioSonics, Inc., Model 101) were used to make background noise measurements at the operating frequencies of the systems. The purpose of these measurements was to determine if sound generated by dredge operations might extend into the portion of the sound spectrum used to make observations of fish distribution and behavior using hydroacoustic instrumentation, potentially negatively impacting such measurements.

A series of three transects were run in the immediate vicinity of the dredge during the morning of September 6, 1995. One transect was run upstream of the dredge, proceeding from the Oregon to the Washington shore, passing closely by navigation buoy 68. A second transect was run immediately downstream of the dredge, starting from the Oregon shore, just offshore of the dredge pipeline discharge location, passing less than 30 feet ($\approx$ 10 m) from the dredge. The third transect was run further downstream from the dredge, starting from the Oregon shore and passing near navigation buoy 66A. The location of the transects is shown in Figure 2.2.

The operational settings and receiving and source levels for the two hydroacoustic systems are shown in Table 2.1. In the table, PAS 103 and BS 101 refer to the Precision Acoustic Systems' and BioSonics' hydroacoustic measurement systems respectively. The systems were operated in passive mode, that is with their transmitters off, so that background noise at 120 and 420 kHz could be measured free from bias due to sound energy that would have been transmitted into the water by the hydroacoustic systems. The systems' transducers were aimed vertically down toward the bottom for all measurements. This method of transducer deployment is typical for kinematic hydroacoustic surveys. Background noise was measured in terms of peak detected voltage out of the systems' receivers at a time delay of 2 ms after opening of the systems' receivers.

Table 2.1. Operating Control Settings for the Hydroacoustic Systems Used to Make Passive Noise Measurements at 120 and 420 kHz

Hydroacoustic System	**PAS 103**	**BS 101**
Source Level in dB re 1μPa at 1 meter	218.32	208.16
Receiving Sensitivity in dBV re 1μPa at 1 meter	-166.83	-171.06
Pulse Width in milliseconds	0.04	0.04
Operating Frequency in kilohertz	122	420
Receiver Time Varied Gain Function	40 Log(R)	40 Log(R)
Transmitter Setting	Off	Off
Receiver Range Gate in meters	30	30
Receiver Gain in dB	+14	+18
Interval Between Transmissions in sec	0.1	0.1
Transducer 3 dB, Full Angle, Beam Width	7°	6°
dB = decibels μPa = micro Pascals dBV = decibel volts PAS = Precision Acoustic Systems BS = Biosonics Systems		

2.3.1.2 Methods for Surface Water Turbidity and Temperature Measurements

Surface water turbidity and temperature measurements were made at approximately equally spaced points along each transect and recorded in a field log. The locations of the measurements were made using a Trimble Navigation Pathfinder ProXL Global Positioning System (GPS) receiver and are reported in latitude and longitude in Table 2.2. GPS estimates of latitude and longitude were post differentially corrected to improve their accuracy to ±1 m.

A nephelometer, LaMotte Model 2008, was used to make turbidity measurements, which are reported as Nephelometric Turbidity Units (NTUs) in Table 2.2 along with surface water temperature (°C). The calibration of the nephelometer was checked in the field prior to use following manufacturer instructions and using manufacturer-supplied standards. Water surface temperature was measured using a laboratory-quality thermometer.

2.3.2 Results

Background noise, surface water turbidity, and surface water temperature measurements obtained on September 6, 1995, in the Jones Beach reach are shown in Table 2.2.

2.3.2.1 Background Noise Measurements

The sonar equation (Urick 1983) was used to estimate the masking threshold equivalents in dB for the measured background noise levels. The levels measured cannot be extrapolated to estimate background source levels for several reasons; however, the objective of the measurements was to determine the response of the hydroacoustic systems to any acoustic noise present and to evaluate measurements made for the potential impact of this noise on the detectability of fish echoes when the systems were operated in active mode.

The hydroacoustic measurement systems used at Jones Beach were configured so that the receivers' time varied gains exactly compensated for the two-way spreading and absorption losses.

Background noise levels at 420 kHz were constant at 50 millivolt (mV) peak (0.050 V-peak, 0.035 V-RMS) along all three transects. By substituting system parameters from Table 2.1 into the sonar equation it was determined that the masking level of background noise in terms of fish target strength was equal to -84.2 dB. This level is approximately 30 dB below a common threshold used for observations of smolt at Columbia River dams (-55 dB). This means that, assuming the conditions during the survey are characteristic of typical conditions in the Jones Beach reach, the ambient sound levels at 420 kHz will not prevent the use of the 420 kHz assessment system for observation of fish near the dredge and at other locations in the Jones Beach reach.

Background noise levels at 120 kHz were more variable than those observed for 420 kHz and showed a contribution from the dredge. Noise levels were observed to double (in terms of peak detected voltage out of the system receiver) at station 2c, which was immediately downstream of the dredge, approximately 10 m from the dredge. The noise level could be observed to increase on approach to the dredge and decrease with distance from the dredge.

The lowest background noise level at 120 kHz, observed upstream of the dredge, was measured to be 50 mV-peak (0.050 V-peak, 0.035 V-RMS). This level corresponds to a masking level of -94.6 dB, which is approximately 10 dB lower than that observed at 420 kHz and approximately 40 dB lower than the target strength threshold typically used to observe salmonid juveniles.

The highest background noise level, at 120 kHz observed immediately downstream of the dredge, was measured to be 100 mV-peak (0.1 V-peak, 0.0707 V-RMS). This noise level corresponds to a masking level of -88.6 dB, which is approximately 35 dB lower than the threshold typically used to observe salmonid juveniles and is also lower than that observed for 420 kHz.

Table 2.2. Location of Sampling Stations and Data Collected at each Station on September 6, 1995

Station	Differentially Corrected Latitude in deg/min/sec	Differentially Corrected Longitude in deg/min/sec	Depth in Feet	Sound Level in mV-Peak		Turbidity in NTU	Temp.
				At 120 kHz	At 420 kHz		
1a	46/8/31.25581	123/17/31.77875	27.2	50	50	4.20	20.0
1b	46/8/34.61690	123/17/30.82922	41.0	50	50	4.10	20.0
1c	46/8/37.57646	123/17/30.24886	50.0	50	50	3.64	20.0
1d	46/8/40.64805	123/17/29.79231	51.5	50	50	3.93	20.0
1e	46/8/44.26875	123/17/29.22856	48.0	50	50	3.75	20.0
1f	46/8/48.53667	123/17/27.85088	48.2	50	50	3.40	20.0
1g	46/8/53.61717	123/17/25.98022	33.5	50	50	3.00	20.0
2a	46/8/28.25623	123/18/19.72228	37.2	70	50	5.10	20.0
2b	46/8/32.77476	123/18/20.59856	52.0	80	50	4.45	20.0
2c	46/8/36.84369	123/18/19.86652	52.5	100	50	3.80	20.0
2d	46/8/40.96311	123/18/22.20777	45.5	70	50	4.05	20.0
2e	46/8/45.69789	123/18/24.12131	30.0	70	50	4.35	20.1
2f	46/8/48.96318	123/18/25.35159	27.0	60	50	3.90	20.0
3a	46/8/27.22577	123/18/47.61821	39.0	70	50	5.85	20.0
3b	46/8/30.87943	123/18/47.93864	51.5	70	50	5.15	20.0
3c	46/8/34.49784	123/18/49.06895	48.0	60	50	3.75	20.0
3d	46/8/40.02020	123/18/51.60560	39.0	70	50	3.72	20.0
3e	46/8/44.77035	123/18/54.54586	28.5	70	50	3.50	20.0
3f	46/8/48.89860	123/18/56.91339	22.0	70	50	3.95	20.0
MV = millivolts							

The equation used for this analysis is shown below.

$$V_{out} = SL + TS - 40\log R - 2\alpha R + TVG + G_{rec} \qquad \text{[Eq. 2.1]}$$

Where: V_{out} = dBv for a target on the transducer acoustic axis

SL = hydroacoustic system source level in dB//1μPa @ 1m

TS = $10\log(\sigma_{bs})$ = target strength in dB

$40\log R$ = two-way spreading loss in dB

$2\alpha R$ = two-way absorption loss in dB

α = attenuation coefficient in dB/m

R = range in m

TVG = hydroacoustic system time varied receiver gain

G_{rec} = hydroacoustic system time invariant gain.

The passive sound measurements show sound generated by the dredge includes energy at ultrasonic frequencies that include 120 kHz. While analysis of the background sound measurements shows that both 120 and 420 kHz can be used in the vicinity of the dredge for observation of fish, caution will have to be used with the 120-kHz system. Hydroacoustic systems utilize very directive transducers and high gain amplifiers since, under normal operating conditions, the energy at the operating frequency of the system scattered back from an ensonified fish, especially a small fish, is on the order of 10^{-6} of the energy incident on the fish. As a consequence, high through-system gain is required to prepare echoes from fish for display and other processing.

In higher noise environments, it is common for some hydroacoustic system transducer aiming angles to show higher background levels than others. The reason for this is straightforward. When the transducer is aimed more directly toward the source of sound, more sound enters the hydroacoustic system. Because hydroacoustic systems are designed to receive and greatly amplify sound within a small band surrounding a specific frequency, any ambient sound within that specific range is amplified and, even for sound sources generating relatively small amounts of sound, ambient sound can mask echo returns from small scatterers such as fish.

Because the dredge emits sound at 120 kHz it is likely that if the hydroacoustic system transducer is aimed directly at the barge, received background noise levels could mask fish echoes. Therefore, if observations of fish are to be made in the vicinity of the dredge when it is operating using hydroacoustic systems operating at 120 kHz, background noise measurements at proposed aiming angles should be measured prior to data acquisition to ensure that echoes from fish will not be masked. Fish echo masking, resulting in large part from acoustic noise at 120 kHz, has been experienced at Columbia River dams and has long been a challenge with vessels (Mitson 1995).

Since background acoustic noise attributed to dredging operations was not found at 420 kHz, the major limitation to hydroacoustic observation of fish at Jones Beach using 420 kHz can be expected to be the reverberation levels received when the system is operated in active mode. Reverberation level is a function of boundary conditions and the characteristics of deployment of the system. The Jones Beach site is above salt water intrusion and has sloping sandy shorelines with no noticeable debris, rock outcroppings, or other features that would scatter sound and complicate deployment of hydroacoustic systems for observation of fish behavior. Negative characteristics of the site are boat traffic and, when the wind blows, surface chop which increases surface scatter, thereby shortening detection ranges for deployments using horizontally aimed transducers. With the exception of avoiding aiming directly at the dredge, limitations outside of those associated with much reduced attenuation due to absorption are the same at 120 kHz.

2.3.2.2 Surface Water Turbidity

Surface water turbidity varied little over the extent of the transects. The range of observations was from 3.40 to 5.85 NTU. The mean and standard deviations across all transects were 4.13 and 0.62 NTU respectively. All measurements made during the survey were in water deeper than 20 feet. While the measurements were made during dredging operations and dredged material was being discharged at the Washington shore, the plume created by the dredging was not detectable in the surface water sampled. However, a plume that closely followed the shore downstream of the discharge point was visible. The plume was inshore of the locations sampled during the survey. Mapping of the plume was not undertaken since it was outside of the scope of the survey and would have required equipment not on hand to sample water at depth.

In July 1994, the Corps sampled the turbidity plume created by dredging operations at Miller Sands in the Jones Beach reach (Field Report, Portland District CE, Appendix A). The dredging operations then were similar to those taking place during the September 6, 1995, survey. Visual observations of plume behavior in July 1994 indicated a plume extending downstream from the point of discharge closely following the shore. Maximum measured turbidity in the plume was 13.9 NTU at the surface, 15.7 NTU at a depth of 5 feet, and 16.9 NTU at a depth of 15 feet. The maximum turbidity measured was 25.8 NTU directly in front of the discharge pipe in an indentation formed in the fill material by discharge from the dredge pipe. Turbidity levels measured outside of the plume were 4 to 5 NTU or similar to values observed in September 1995.

2.3.2.3 Surface Water Temperature

The surface water temperatures observed were uniform at 20° C. This temperature is consistent (within ± 1° C) with weekly mean water temperatures observed during September at Jones Beach 1977-1983 (Dawley et al. 1985a and b).

2.4 Discussion

The following conclusions and recommendations are based on literature reviews we conducted of salmonid migratory behavior in the Jones Beach reach and salmon response to turbidity plumes and sound fields, as well as observations and hydroacoustic measurements we conducted of dredging operations at the Jones Beach reach in September 1995 as described above.

2.4.1 Conclusions

Information from the literature review indicates that migrating juvenile salmonids are present within the entire cross section of the Jones Beach reach, especially the upper 10 feet of the water column during their outmigration period. Smaller migrants, predominately fall chinook, are found nearer the shore with the majority located within the 10-foot depth isopleth. Yearlings and larger migrants (>≈ 80 mm in length) are usually found offshore, including the main channel region. Juvenile salmonids appear to be most actively migrating during the day. While most juvenile migrants pass through the Jones Beach reach during the months of April through August, juvenile salmonids can be found in the reach most of the year.

Our observations of dredging operations at Jones Beach reveal that dredging is conducted 24 hours a day and involves the use of several types of equipment. Peak activity is during the day as the dredge is moved between locations and maintenance activities are performed. Regardless of where dredging is being conducted within the navigation channel, the pipeline carrying dredged materials to the shore crosses, either above or below water, a portion of the river cross section utilized by migrants. This means that migrating fish passing on the side of the river where disposal is taking place have a high likelihood of encountering the pipeline or the dredge.

Experimental data reported in the literature suggest that relatively large displacements within a rather narrow range of infrasound frequencies are required to generate a stimulus resulting in an avoidance response by juvenile salmonids. Juvenile salmonids have been shown to exhibit startle and avoidance responses with essentially no habituation to the hydrodynamic component of the near field of a volume displacement source operating at infrasound frequencies (i.e., < 20 Hz). The relevant stimulus has been identified in recent laboratory and field studies as water particle acceleration. Stimulus thresholds for salmonid avoidance response have been determined to be $\geq 10^{-2}$ m/sec^2 at 10 Hz (Knudsen et al. 1992, 1994, 1997).

No sound field measurements have been made in the vicinity of the vessels, dredges, and other marine construction equipment of the hydrodynamic component in the near field of the various sound sources. Also, there is no direct and unambiguous way to use measurements made in the far field of a sound source using pressure sensitive devices (hydrophones) to estimate any other than the most general of the characteristics of the near field of sound sources.

Visual observations of the pipeline and its supporting tanks did not detect any large vibratory movements suspected as significant sources of volume displacement infrasound. However, potential sources may have been missed because observations were made over a short time period. In addition, it was not practical, given the scope of the study, to conduct an extensive survey of the dredge itself to look for potential infrasound sources.

In addition to looking at salmonid response to sound we also investigated potential avoidance response to turbidity. Deposition of fill material on the beach causes the creation of a turbidity plume that appears to remain quite close to the shore (within 50 to 75 feet) and extends downstream from the point of discharge approximately 1,500 feet. Visual observations of the turbidity plume generated by dredging operations in September 5-6, 1995, and measurements by the Corps in July 1994 of turbidity in surface waters at depths greater than 20 feet appear to confirm the conclusion of previous studies that in general the “dredge-induced turbidity plume can be described as a ‘near-field’ phenomenon.”

The turbidity values observed in September 1995, as well as those observed by the Corps in July 1994, are in the range of 0-20 NTU, which is considered “lower turbidity” (Sigler 1988). Reviews of the likely effects of these levels of turbidity can be found in Sigler (1988) and Feist and Anderson (1991). Based on limited measurements of turbidity within the discharge plume, it appears that turbidity levels are well below sublethal and lethal effects. The highest turbidity levels observed were below those known to stimulate avoidance response by juvenile salmonids. Servizi and Martens (1992) estimated the threshold for avoidance in the vertical plane for juvenile coho and steelhead at 37 NTU. Other researchers have observed that the turbidity level to which coho salmon are acclimated affects the turbidity level they will avoid. Coho acclimated to < 0.3 NTU initially avoided turbidity levels of 70 NTU but quickly acclimated to these significantly higher levels (Bisson and Bilby 1982). In general, it appears that the moderate increase over ambient turbidity from Jones Beach reach dredging operations is below levels shown to influence fish behavior.

It is interesting that the observed turbidities in the dredge plume occur elsewhere in the Columbia River basin as a result of agricultural drainage and normal runoff. Turbidities as high as 20 NTU are common through the irrigation season (April through September) within the Columbia River Basin in tributaries such as the Yakima River (Dauble et al. 1994). Thus it is likely that a portion of the migrants coming through the Jones Beach reach may have already experienced turbidities as high as or higher than those existing in the dredge turbidity plume.

The location of the turbidity plume provides for hydroacoustic observation of the behavior of migrants in the immediate vicinity of the plume. The higher turbidity portion of the plume could be ensonified by transducers located near shore aimed horizontally into the river. The smooth, sandy sloping shoreline would make it feasible, during periods of low surface chop, to observe fish out to ranges of 100 feet or more. Split-beam hydroacoustic methods could be used to obtain three-dimensional estimates of the location of fish in the water column. The behavior of fish within the plume compared to locations upstream and downstream of the plume could provide information about avoidance of the plume by migrants. Hydroacoustic observations could be supplemented by a small amount of physical capture using beach seines to identify the species and size of fish observed.

Routine operations at the dredge make it unsuitable as a location for hydroacoustic instruments. The majority of smaller salmonid migrants have been found to pass through the reach within the 10 ft contour (Dawley et al. 1986). It is unlikely that hydroacoustics deployments of reasonable size would be capable of sampling a sufficiently large segment of the cross section outside of the 10-foot-depth contour to obtain a representative sample of the migratory behavior of larger juvenile salmonids. It is likely that other behavioral observation methods such as ultrasonic 3D tracking will be required to obtain observations of the impact of dredging operations on juvenile salmonids in the offshore portions of the reach.

2.4.2 Recommendations

Studies need to be conducted to characterize the sound field generated by dredging activities and to determine what proportion is an effective stimulus for salmonid avoidance response. Systematic and thorough hydroacoustic measurements with appropriate instrumentation will be required to map the sound fields generated by dredging activities and to identify the sources of those fields.

Field surveys of dredges and other marine construction equipment should be conducted to identify equipment in contact with the water that may generate hydrodynamic fields capable of stimulating salmonid avoidance. The value in identifying the sources, in addition to mapping the fields they generate, is that it might be possible to modify the design or operation of the equipment to reduce or eliminate the generation of the stimulus field. An inventory of dredging, pile driving, and other equipment might determine that only a relatively few types of equipment under certain operational modes are capable of generating avoidance stimuli.

Direct observations of migrant behavior in and near the plume are needed to test hypotheses about migrant avoidance response because the range of turbidities from ambient to the highest observed in the plume is smaller than those used in laboratory experiments where avoidance responses were observed. It will be necessary to use observational methods, such as ultrasonic 3D tracking that permit fish location to be estimated in three dimensions relative to the plume, given the three-dimensional nature of the turbidity plume, and to obtain measurements of turbidity, including mapping of the plume, concurrent with observations of fish behavior.

3.0 The Behavior of Fish in the Vicinity of a Pile Dike in the Lower Columbia River[(a)]

The purpose of this study was to observe fish behavior in the immediate vicinity of a pile dike and to determine whether there were differences in behavior between daytime and nighttime.

3.1 Study Methods

The behavior of fish in the immediate vicinity of a pile dike located at Jones Beach on the lower Columbia River was observed over several consecutive 24-hour periods from July 26 to August 5, 1996, using standard single-beam hydroacoustic methods.

Six hydroacoustic transducers were located along the pile dike, three on each side of the dike. All the transducers were aimed horizontally into the water column so that their acoustic axes were on an angle of 60° to the dike. On each side of the dike, two transducers, one located approximately one-third of the length of the dike offshore and another located at the midpoint of the dike, were aimed toward the navigation channel. The third transducer, located near the end of the dike closest to the navigation channel, was aimed toward the shore. These transducer locations and aiming angles provided sampling near shore, along the pile dike, and at the end of the pile dike with some sample volume within the navigation channel.

3.2 Results

The behavior of fish within the immediate vicinity of the pile dike differed from day to night. The daytime and nighttime behavior of the observed fish is summarized in Figures 3.1 and 3.2. The figures show the net direction of movement of fish through the sampled acoustic volumes over the period of the study. While the hydroacoustic methods used for the study permit detailed observations of fish behavior to be made over long periods of time without impacting fish, they do not provide information about the species composition or other biological information about the observed fish. Therefore, the observations are for the whole fish population in the vicinity of the pile dike during the period of study. However, during this time of year, summer run salmon smolt are historically a major portion of fish in the river at Jones Beach (Dawley et al. 1986). For this reason the observed behavioral trends are believed to represent the general behavior of the summer run smolt that passed by the pile dike during the period of study.

During the day (Figure 3.1), the majority of fish present near the end of the pile dike, on both the upstream and downstream sides of the dike, were moving downstream. These fish apparently passed downstream by moving around the end of the dike utilizing the navigation channel or, most likely to a lesser extent, passed through the dike. Milling activity was indicated on the upstream side of the dike as the distance from shore decreased. On the downstream side of the dike net movement was upstream

(a) This study was conducted by T.J. Carlson, while at the U.S. Army Corps of Engineers, Waterways Experiment Station, Stevenson, Washington, in July and August 1996.

toward the dike. This indicates that fish hold on the downstream side of the dike, most likely taking advantage of the decrease in water velocity due to the presence of the dike.

The behavior patterns observed during the night were quite different from those observed during the day (Figure 3.2). Along the end of the dike nearest the navigation channel, the net downstream movement of fish was almost exactly the opposite of that observed during the day. That is, the majority of fish were observed moving through the ensonified volumes in a general upstream direction. Given the behavioral patterns observed within the other ensonified volumes, the fish moving in an upstream direction through the ensonified volumes nearest the navigation channel are most likely fish moving shoreward while maintaining some upstream net motion rather than a reverse migration upstream by juvenile salmonids. While the milling behavior observed during the day near shore upstream of the dike was also observed during the night, behavior downstream of the dike at night was quite different from that observed during the day. At night, downstream of the dike, fish appeared to aggregate with net flux into the region behind the dike, represented by a negative net downstream flux on one transducer and near zero flux on the second transducer monitoring the nearer shore region downstream of the dike.

3.3 Observations and Discussion

The results of this study show that pile dikes are structures within the river that fish respond to differently during the day and at night. The regions with the most pronounced differences in behavior are the section of the dike nearest the navigation channel and that nearer shore downstream of the dike. During the night there appears to be a significant decrease in the downstream movement of fish near the offshore end of the dike accompanied by a general movement inshore of the composite fish population into the area downstream of the dike where water velocities would be lower. The behavioral observations made during this study appear consistent with the conclusions about fish behavior drawn from beach seine sampling conducted during the summer smolt outmigration from 1966 through 1983 at Jones Beach by Dawley et al. (1986). Based on extensive beach seine samples, these investigators concluded that summer run migrants in general tended to hold at night, continuing their downstream migration at dawn.

Assuming a significant portion of the fish observed hydroacoustically during this study are summer run juvenile salmonid migrants, pile dikes provide structure that salmonid migrants use during their downstream migration.

4.0 Characterization of Underwater Sound Generated by Impact Pile Driving within the Context of the Response of Salmonid Smolt to Impulsive Sound, 1996[(a)]

Construction and maintenance of pile dikes and related maritime construction activities are an integral part of navigation channel maintenance. Within the Columbia River, such construction activities are regulated to reduce potential impacts to migrating steelhead and salmon smolt, some of which are listed under the Endangered Species Act.

The times and locations for pile driving activities are regulated in part because of concern that the underwater sound generated by pile driving may detrimentally affect the migratory behavior of salmon and steelhead smolt. Within the last decade, advancements have been made in identifying the characteristics of sound that elicit an avoidance response from salmonids and that are effective in excluding salmonids from regions where the intensity of effective sound signals is high. These results, in conjunction with others, permit evaluation of the likely impact of underwater sound generated by pile driving activity on smolt migratory behavior.

Replacement of piles along an existing pile dike near Altona, Washington, on the lower Columbia River offered an opportunity to obtain measurements of the underwater sound generated by impact pile driving. Two days of sampling were conducted, October 3 and November 1, 1999.

4.1 Materials and Methods

Sound field measurements were made over a two-day period, October 31 and November 1, 1996, at a pile dike repair underway on the Washington shore of the Columbia River upstream of Altona, Washington. The pile replacement activity consisted of placing pilings at locations along the existing pile dike where individual piles had eroded and were no longer functional. The replacement piles were approximately 60-ft-long by one-ft-diameter wooden piles.

Pile driving was conducted using two barges and a work tug. One barge was used to store work materials including piles. The other barge held a crane and various tools needed to support the pile driver. The pile driving activity consisted of a repetitive series of activities which began with lifting a pile from the staging barge, fitting the hammer to the top of the pile, placing the pile using the template, and driving in the pile. Driving of piles was accomplished quite quickly once all preparations were complete.

All underwater sound measurements were made from the corner of the barge where the piles and other work materials were stored. This location permitted all measurements to be made within 30 feet of the piles being driven. In addition to providing a stable measurement platform, the barge also provided shelter for the hydrophone, reducing the impact of surface waves on data acquisition procedures.

(a) This study was conducted by T.J. Carlson, while at the U.S. Army Corps of Engineers – Portland District, Waterways Experiment Station, Stevenson, Washington, in 1996.

The equipment used to acquire and process the sound signals is given in Table 4.1 below. The hydrophone, charge amplifier, and DAT (digital audio tape) recorder were used to acquire and store raw sound signals as the piles were being driven. The signal processing hardware and software were used to process and analyze the acquired signals under laboratory conditions at a later time.

Table 4.1. Instruments Used to Acquire, Process, and Analyze Underwater Sound Signals

Instrument	Manufacturer	Model No.
Hydrophone	Bruel & Kjaer	8104
Charge Amplifier	Bruel & Kjaer	2635
Digital Audio Tape Recorder	Sony	PC204Ax
Signal Processing Digital Acquisition Board and Software	National Instruments	DSP-2200, Joint Time-Frequency Analysis Toolkit

The frequency response of the B&K 8104 hydrophone is flat from 1 Hz to 10 kHz. Over this range its receiving sensitivity is 53.7 µV/Pa and its directivity is essentially omnidirectional. The B&K 2635 charge amplifier is designed so that the calibration constant for the hydrophone can be input to the amplifier, thereby permitting the amplifier output to be read directly in terms of pressure in Pa. The charge amplifier also permits control of the gain of the output signal so that the dynamic range of the DAT recorder can be optimized. The frequency range of the Sony instrumentation digital audio tape recorder is DC to 20 kHz. The frequency response of the recorder over this range is flat.

The hydrophone cable was attached to a line marked in foot increments so that the hydrophone could be easily deployed at any depth to 30 feet, the length of the hydrophone cable, while keeping the hydrophone cable free of any load. The hydrophone was held in position by a weight attached to the bottom of the line supporting the hydrophone cable and a buoy attached to the line at the surface. The buoy was attached to the line by a snap so that its position could be changed to permit positioning of the hydrophone at different depths.

Over the two days sampling was conducted, driving of 16 piles was monitored. Additional observations were made of the background sound levels present in the absence of pile driving activity. The measurement procedure was to initiate tape recording of the output of the charge amplifier at the time the pile was lowered into position by the crane and prior to the onset of driving. Monitoring continued through driving of each pile and for a short time after the impact hammer was lifted from the pile.

Table 4.2 below shows the identification number of the piles driven, the range from the hydrophone buoy to the pile, the depth of the hydrophone, the start and stop times for each pile, and the time required to drive each pile.

Table 4.2. Distance of Monitoring Hydrophone from Each Pile and Time Required to Drive Each Pile

Pile ID Number	Pile to Hydrophone Range in Feet	Hydrophone Depth in Feet	Pile Driving Start Time in HHMMSS	Pile Driving End Time in HHMMSS	Time Required to Drive Pile in HHMMSS
1031:001	30	5	141850	141930	000040
1031:002	25	15	143325	144020	001055
1031:003	22	10	144756	1445347	000551
1031:004	25	20	150510	150930	000420
1031:005	28	20	151556	152153	000557
1031:006	30	20	152750	123448	000502
1031:007	30	20	154130	154945	000815
111:001	25	10	113354	114150	000756
111:002	27	5	114940	115409	000429
111:003	27	15	115707	120030	000313
111:004	20	10	120610	121620	001010
111:005	20	5	122222	122331	000109
111:006	25	15	123940	125100	001120
111:007	30	5	125700	130725	001025
111:008	30	10	131249	132530	001241
111:009	25	15	132930	134448	001518
HHMMSS = hours, minutes, seconds					

All of the underwater sound measurements were made at one of four depths: 5, 10, 15, or 20 feet. The 20-foot depth was only available near mid-tide, approaching the time in the daily tidal cycle when pile driving activities had to be discontinued for the day due to submergence of the portion of the pile dike being repaired. This sampling strategy was selected to obtain sound measurements near the surface and bottom boundaries in addition to mid-water. Although the distance between the piles and the hydrophone was short, it was unclear what effect, if any, the surface and bottom might have on the sound field. The sampling method implemented permitted observation of the sound field generated by impact pile driving over the vertical range available to fish. While the use of a single hydrophone to sample a complex three-dimensional sound field is limiting, the observations obtained are representative of the sound field generated by impact pile driving.

The recorded sound measurements were processed using a National Instruments Joint Time-Frequency Analysis (JTFA) and a Virtual Bench Digital Signal Analysis (DSA) software tool kit and a DSP-2200 digital data acquisition board. The software program SAS Signal was also used for some analyses. Underwater sound signals from the pile driving were digitized by taking 512 measurements at a sampling rate of 4 kHz. The toolkits and digital acquisition board filtered the data prior to digitization to remove frequencies higher than the Nyquist frequency at the 4 kHz sampling rate.

The output of the DSA-JTFA tool kits and SAS Signal included a joint frequency-time power spectrum (time-dependent frequency spectrum) and time domain waveform in a spreadsheet format. The sound signal tape recording for each of the piles was sampled a minimum of five times at locations approximately equally spaced throughout the driving time for each pile. Following review of the plots of time domain waveforms, a single waveform was selected as representative of those for the pile and was analyzed using the JTFA. This analysis produced a joint frequency-time power spectrum for the selected waveform. All of the input data for the JTFA analysis, including the other time domain waveforms, were placed in Microsoft Excel workbooks organized by pile. Using Excel functions, the time domain waveforms were adjusted to compensate for DAT recorder gain and differences in charge amplifier settings between piles. Because of the time required to process the data for each pile, a subset of piles from the total monitored was selected for complete analysis.

4.2 Results

4.2.1 Time to Drive a Pile

Certain elements of the repair work on the pile dike at Altona, including driving of the piles, could only be performed during those tidal stages when the water was low enough to expose a sufficient portion of the pile dike. In addition to this limitation, which restricted the period during each day when work could be performed, considerable time was required to set up a series of piles for driving. As a consequence, piles were being driven, and therefore underwater sound was being generated, for a relatively short period within a typical work period.

The sequence of events in placing a pile are 1) attach a cable to a pile and lift the pile, 2) with the aid of a spotter and template, position the pile in the desired location, 3) place the impact hammer on top of the pile, 4) set the pile with one or two hammer blows and recheck its position and aspect, 5) once correctly positioned, drive the pile, and 6) remove the hammer from the pile. The time required for these activities was very consistent between piles with the exception of #5, driving the pile. The range in time required to drive a pile varied from approximately 1 minute to approximately 15 minutes (Table 4.2). Driving time seemed to be the result of the composition of the material into which the pile was being driven, although other factors such as the angle of the pile and the resulting inefficiencies in transfer of energy from the hammer to the pile also likely influenced driving time. Even within a short distance along the dike there appeared to be considerable differences in substrate material or other subsurface conditions that influenced the time required to drive a pile.

4.2.2 Background Sound Level and Spectral Composition

A series of five samples of the background sound at the construction site was taken at the onset of sampling on 11/1. The pile driving crew had been at work for approximately 1 hour preparing to drive the series of piles planned for the day when the measurements were made. No pile driving activity occurred during the background measurements. The pressure waveforms corresponding to the samples analyzed show peak pressures of approximately 60 Pa (Figure 4.1). The waveforms include changes in local pressure at the hydrophone due to surface waves and other non-sound phenomena in addition to pressure changes due to sound. The changes in pressure at the hydrophones due to water surface elevation changes are the very low frequency (slowly changing) component of the time domain signal. Figure 4.2 is a single time domain signal selected at random from those shown in Figure 4.1. The frequency spectrum and time-frequency contour plot of this signal are shown in Figures 4.3 and 4.4 respectively. The time-frequency plot as well as the power spectrum show that most of the background energy within the 0 to 250 Hz frequency range is located between 0 and 20 Hz. The higher frequency component of the sound signal has a very noticeable peak at approximately 265 Hz. This peak is well above the 150 Hz upper limit for hearing in salmonids (Hawkins and Johnstone 1978; Kalmijn 1988).

4.2.3 Sound Generated by Pile Driving

The basic characteristics of the pressure waveform generated by individual hammer impacts were very consistent for individual piles and showed distinctive differences between piles while retaining similarity in general form. Figures 4.5, 4.9, 4.13, 4.17, and 4.21 show the pressure waveforms for the individual hammer impacts sampled for piles 1, 2, 3, 4, and 5 respectively. Each figure shows at least five individual hammer impacts for each pile.

For all of the piles, each hammer impact is characterized by an initial pulse approximately 40 ms in duration. The duration of the initial pulse following hammer impact is quite consistent for all hammer impacts analyzed. The initial pulse is characterized by high peak pressures (relative to the rest of the waveform) at initial contact followed by a decrease until pressure levels approach background pressure levels. For several of the piles, a second pulse, resulting from the hammer "bouncing" after the initial impact and striking the pile driver, occurs within 50 to 100 ms of the initial impact. In addition, four of the five hammer blows analyzed show a low frequency component following the initial high energy sound pulse. This low frequency component is probably due to the lateral movement of the pile following impact. It is also possible that there may be some bending of the pile that contributes to generation of this part of the underwater sound signal. Within 125 ms of the initial impact, for all the hammer blows examined, the sound event created by the hammer blow had passed and pressure levels were again at background levels. During the monitoring period, the impact hammer was operated at a rate of two blows per second. Given the time required for return to background levels following impact, in conjunction with the repetition rate of the hammer, sound generated by hammering was present in the water column approximately 25% of the time (0.250 sec) during pile driving.

The peak pressure generated by the impacts varied from a low of approximately 110 Pa (160 dB//μPa) to a high of 6,000 Pa (195 dB//μPa). Impact peak pressures for four of the six piles were very similar between 1,500 (183 dB//μPa) and 2,000 Pa (186 dB//μPa).

Individual waveforms for each pile were randomly selected for spectral analysis from the five available for each pile. The selected pressure waveforms are presented in Figures 4.6, 4.10, 4.14, 4.18, and 4.22 corresponding to piles 1, 2, 3, 4, and 5. The pulse duration and peak pressure for the individual waveforms are consistent with those described above for all of the waveforms for each pile. Close examination of the pressure waveforms shows structure in the initial and secondary pulses (when present) that is similar from pile to pile. The periodic structure in the pulse is likely the result of complex interactions between the hammer and the pile as it responds to the hammer blow, which could include pile movement such as bending and other lateral motion in addition to the vertical movement into the river bottom. Figures 4.7, 4.11, 4.15, 4.19, and 4.23 are frequency spectrums for impacts shown in Figures 4.6, 4.10, 4.14, 4.18, and 4.22.

The individual pressure waveforms were analyzed to obtain frequency time spectra within the band 0 to 500 Hz. The frequency spectra time-frequency contour plots corresponding to the individual pressure waveforms presented earlier are shown in Figures 4.8, 4.12, 4.16, 4.20 and 4.24. As expected from visual examination of the pressure waveforms, the frequency content of the initial and secondary higher frequency pulses is similar for all piles. Peaks in the power spectra occur for all piles at frequencies between approximately 125 and 810 Hz. Almost all of the energy in these portions of the sound signal is above the upper frequency in the hearing bandwidth for salmonids, which is 150 Hz (Hawkins and Johnstone 1978; Kalmijn 1988). The band below 30 Hz contains the background “noise” in the pressure spectra plus some limited contribution from the initial hammer impact and secondary characteristics following the initial impact pulse.

Figure 4.25 shows several pressure waveforms generated by a volume displacement infrasound source. The waveforms are very uniform in shape. Figures 4.27 and 4.28 show the frequency spectrum and joint time-frequency contour plot respectively of one of the waveforms shown in Figure 4.15, which is shown in Figure 4.26. Figure 4.27 shows that almost all of the energy in the output of the volume displacement source is below 20 Hz with the peak in energy located at 12.4 Hz. This device was designed to operate at 12 Hz.

4.3 Discussion

Considerable progress has been made in the last 25 years in understanding what salmonids, and other fish, can hear and their behavioral response to what they hear (Carlson 1994; Popper and Carlson 1998). The basic audiogram for salmonids was determined in 1978 (Hawkins and Johnstone 1978) and recast by Kalmijn (1988) to take into consideration the physical stimulus, water particle acceleration, to which the salmonid inner ear and lateral line respond. Kalmijn’s analysis showed that salmonid hearing is most sensitive below approximately 150 Hz, retaining maximum sensitivity through the infrasound region.

Repeatable avoidance responses by Atlantic and Pacific salmonids and steelhead, in addition to many other species, have been obtained under both laboratory and field conditions (Knudsen et al. 1992, 1994; Taft et al. 1994; Knudsen et al. 1997; Mueller et al. 1998). The effective stimulus has been identified to be the local flow component of infrasound in the range of 5 to 30 Hz where water particle acceleration is greater than 0.01 ms^{-2}. The effective stimulus for avoidance response is only found in the near field of sources capable of generating a local flow field with water particle acceleration greater than the above threshold. The effective stimulus for avoidance response by salmonids does not exist in the far field of any source or in the near field of sources that do not have significant displacement amplitudes (i.e., greater than 0.01 m) of their active element.

Higher frequency elements of the sound signal were observed resulting from small movements of the piston as it moved within its cylinder during operation of the pile driver. The source that generated this waveform has been demonstrated to create a local flow infrasound field eliciting avoidance response from salmon and steelhead (Mueller et al. 1998; Knudsen et al. 1997). An avoidance response resulting in exposed fish actively swimming away from the infrasound source typically requires several seconds of exposure. Laboratory and field studies that have demonstrated a consistent avoidance response from salmonids and other fish use infrasound signals that are 4 to 6 seconds in duration. These studies have also shown that exposed fish habituate with continued exposure but recover from habituation within short periods of no exposure.

Research has shown that it is not the propagated sound field that salmonids respond to, but rather the local flow in the near field of the sound source. The effective stimulus is water particle acceleration on the order of 0.01 ms^{-2} at infrasound frequencies. Several seconds of continuous transmission is required to "push" salmonids out of the immediate near field of a volume displacement infrasound source, a distance of 3 to 5 meters for those sources tested. This means that it is likely that many infrasound sources do not generate the necessary stimulus for salmonid avoidance even though they may generate a detectable propagating infrasound sound field. It also means that, even in the case of those sources of infrasound that are energetic enough to generate a local flow field with water particle accelerations of sufficient magnitude, the range over which the stimulus (water particle motion) is above threshold levels will be small, on the order of a few meters. The additional requirement of several seconds of continuous exposure for a sustained avoidance response means that it is very unlikely that most impulsive sound sources, even those that are higher energy like pile driving, will elicit an avoidance response from salmonids sufficient to impede migratory behavior.

During the search over the past few decades for stimuli that could be used at field scales to modify the behavior of unconditioned salmonids, a variety of impulsive sound sources have been tested. Some of the more extensively tested have been sound sources used by the geophysical survey industry to generate high-energy, low-frequency sound for exploration of oil and gas. Geophysical sound sources come in a variety of forms; however, all have sound production characteristics similar to the sound impulses generated by impact pile driving. As an element of a study to evaluate the effects of marine geophysical surveys on rockfish fishing success (Pearson et al. 1987), the sounds generated by geophysical survey devices were determined (Malme et al. 1986). The study examined air guns, water guns, gas guns, and electrical sparkers plus a few less common devices. Typically the pressure waveform generated by any these devices consists of an impulse approximately 20 ms long with peak-to-peak pressure values within the range of 220 to 245 dB//μPa (100,000 to 1,800,000 Pa). In comparison, the estimated peak source level for a 1-pound charge of TNT was estimated by Malme et al. (1986) to be 267 dB//μPa (22,400,000 Pa). The high-energy pressure waves with very rapid rise times (on the order of microseconds) resulting from explosions have been shown to damage fish and can kill fish when they are near the source (Hill 1978).

In contrast, lethal effects have not been observed to result from exposure to geophysical sound sources. The spectra of the sound impulses generated by geophysical devices tend to be similar to those for impact pile driving based on the spectra presented by Malme et al. (1986). In general, it appears that the peak-to-peak pressure values for geophysical sources are at least 20 dB (a factor of 10) higher than those for impact pile driving (at least for the underwater sound generated by the pile driving observed at Altona). The maximum peak-to-peak pressure values observed for impact pile driving in this study were approximately 200 dB//μPa, (10,000 Pa) with the typical value being approximately 192 dB//μPa (4,000 Pa), considerably less than those for the geophysical sound sources. A feature present in several of the spectra is energy below 30 Hz associated with movement of the pile between the initial and second impacts and associated sound pulses. The importance of this component of the sound generated by impact pile driving is that it is within the range of frequencies (< 30 Hz) shown to elicit avoidance responses by salmonids (Knudsen et al. 1992, 1994, and 1997).

While the sound fields generated by geophysical sources have been shown to affect the catchability of rockfish (Pearson et al. 1987), as well as cod and haddock (Engas et al. 1993), laboratory and field level experiments have demonstrated that impulsive sound sources are ineffective in stimulating a sustained avoidance response by salmonids (Carlson 1994; EPRI 1986; Bengeyfield and Smith 1989). As a result of this finding, impulsive sound sources are no longer being pursued as a potential means for modifying the behavior of salmonids.

The data characterizing the sound field generated by impact pile driving obtained in this study, evaluated in the context of experience with geophysical sound sources and in that of recent experience with near field infrasound, indicates that impact pile driving does not produce an adequate stimulus for sustained avoidance responses by salmonids. There are several facts leading to this conclusion: 1) the total time of sound generation by impact pile driving is short, extending approximately 125 ms in total from the instant of impact, with the majority of the sound energy being produced within the first 5 ms, 2) the frequency of hammer impacts is two per second resulting in sound production approximately 25% of the total time during pile driving, 3) the maximum instantaneous peak-to-peak pressure values in the primary impulse following hammer impact are below 200 dB//µPa, levels well below that of geophysical sound sources extensively laboratory and field tested and found not to be effective in stimulating a sustained avoidance response by salmonids, 4) inspection of pressure waveforms shows that infrasound frequency components are typically associated with the primary and secondary impulses from individual hammer impacts and are not similar to the well-formed sinusoidal infrasound stimuli demonstrated to stimulate a sustained avoidance response by salmonids, and 5) most of the energy in the hammer impact impulses is contained at frequencies around 200 Hz and higher, above the region of maximum hearing response by salmonids.

5.0 Observations of the Behavior of Fish Relative to the Columbia River Navigation Channel and Channel Maintenance Activities in 1997[a]

Mobile hydroacoustic surveys were conducted during the spring juvenile salmon outmigration (May 19-22, 1997) and during the summer out migration (July 22-24) to monitor fish distribution across the river upstream and downstream of a channel maintenance dredge.

5.1 Study Methods

5.1.1 Mobile Hydroacoustic Surveys

During the spring outmigration (May 19-22, 1997), a BioSonics DT 6000 Scientific Digital Echosounder was used to transmit 420-kHz sound from a 6-degree split-beam transducer mounted on a BioSonics Biofin and deployed from a boom off the bow of a 24-ft boat. The ping rate during sampling was 10 pings per second at a maximum depth of 25 m. The sounder was controlled with BioSonics split-beam software running on a 66-MHz 486 NEC laptop computer with a BioSonics Echo Signal Processing (ESP) board. Position was recorded using a Trimble Pathfinder Pro-XL geographical position system (GPS) and linked with OMNISTAR to differentially correct and provide real-time submeter accuracy. Data was collected from Westport Slough downstream to Welch Island and upstream to the east end of Puget Island (Figure 5.1 and 6.1).

In the summer the mobile hydroacoustics system consisted of a Model 103 echosounder and a 6-degree 420-kHz split beam transducer manufactured by Precision Acoustic Systems (PAS) Incorporated of Seattle, Washington. The system was controlled by a Gateway 120-MHz pentium computer and HARP software developed by Hydroacoustic Assessments of Seattle, Washington. The transducer was pinged at 15 pings per second. GPS data was collected with the same system as was used in the spring. Data was collected from below Westport Slough to Welch Island (downstream) and above Puget Island to Wallace Island (upstream) (Figure 5.2).

We were unable to sample the top 2.75 m of the water column due to a 2-m receiver blanking range, and because the transducer was mounted 0.75 m below the surface. Criteria for accepting echo traces as fish was 4 to 20 echoes per trace. The numbers of tracked fish were expanded for beam width to normalize for depth:

Expansion factor = MD / (2 * DD * (TAN(4))) [Eq. 5.1]

(a) This study was conducted by T.J. Carlson, while at the U.S. Army Corps of Engineers – Portland District, M.A. Weiland while with AScI Corporation, and G.R. Ploskey while with the U.S. Army Corps of Engineers at the Waterways Experiment Station.

where:
MD is the maximum diameter of the beam,
DD is the beam diameter at the fish distance from the transducer,
TAN is the tangent, and
4 is the effective beam half angle.

The maximum effective beam angle for the transducers was estimated to be 8 degrees.
Spring data collected with the Biosonics split-beam system was manually tracked using the BioSonics Visual Analyzer. Summer data was processed using a Visual Basic tracking program developed by the USACE (Bill Nagy, Fishery Field Unit, Portland District, US Army Corps of Engineers, Portland, Oregon). The data was then analyzed using SAS (Statistical Analysis System).

5.1.2 Fixed-Aspect Hydroacoustics

The two split-beam hydroacoustic systems used during the spring and summer mobile surveys were deployed at Westport Bar (Jones Beach) at the west end of Wallace Island, above (PAS system) and below (BioSonics DT6000) the dredge spoil outflow pipe. Data was collected July 25, 1997, between 0400 and 0800 hours during dredge operation. The PAS split-beam transducer was mounted about 100 m above the outflow and pinged at 15 pings per second with a maximum range of 30 m. The BioSonics split-beam transducer was mounted about 50 m below the outflow and pinged at 10 pings per second with a maximum range of 15 m. The transducers were mounted horizontally in about 1.5 m of water so they were aimed across the river.

5.1.3 Environmental Data

During the hydroacoustic data collection, terrestrial light and air temperature readings were recorded at 5-minute intervals using a LI-1000 Data Logger from LI-COR Inc. of Lincoln, Nebraska. Light levels were measured with a LI 210SA photometric sensor. Turbidity levels were collected during dredging using a LaMotte Model 2008 Turbidity Meter from LaMotte Company of Chestertown, Maryland. Three water samples were collected during hydroacoustic sampling and turbidity levels were read immediately.

5.2 Results

5.2.1 Mobile Hydroacoustic Surveys

The fish distribution statistics given below are proportions within that portion of vertical dimension of the volume sampled. The volume sampled does not include the upper 2.5 m of the water column and that portion of the bottom within the echo sounder's pulse resolution volume (approximately 0.5 m).

In the spring, 15.3% of detected fish were located in the channel, 55.5% were in the channel margin, and 29.2% were near the shore. A significant relationship was not found between fish depth and time of day.

In the summer at the downstream section, 31.7% of the detected fish were in the channel, 42.1% were in the channel margin, and 26.2% were near the shore. There was a significant difference in the number of fish found in each of the three habitats ($P<0.05$). At the upstream section, near the dredge, 21.7% of the fish were found in the channel, 63.3% were in the channel margin, and 15.0% were near the shore. There was also a significant difference in fish densities between all habitats (P<0.05).

Fish densities were higher above the dredge than below in the channel and at the channel margin. But numbers were higher near shore below the dredge. These differences were not significant though (P>0.05). Densities were also found to be highest on the Oregon (south) side of the Columbia River, but were not significantly different (P>0.05) from those observed on the Washington (north) side of the river (Table 5.1).

In summer, at the downstream section there was not a significant relationship between light level and fish depth in any of the three habitats. No significant relationship was found between light level and fish depth in the channel or channel margin. At the upstream section, however, a significant relationship was found between light level and fish depth near shore, where densities were higher near the surface during the day and were deeper at night (Figure 5.3).

5.2.2 Fixed-Aspect Hydroacoustics

During the four-hour sampling period, 255 fish per hour were detected passing above the dredge outflow through the upstream transducer beam, which had a range of 30 m. Only 1 fish was detected below the dredge outflow with the downstream transducer, which had a range of 15 m. After expanding for acoustic beam the expanded number of downstream fish was only 1.8. We recalculated the upstream number to county only fish within 15 m of the transducer. The recalculated number was 224 fish per hour upstream. Average turbidity was 6.15 NU above the dredge spoil outflow and 21.6 NU below the outflow.

Table 5.1. Percent Contribution of Fish by Habitat and Side of River, Above and Below a Dredge

Habitat	Reference to Dredge	Side of River	Percent of Fish
Channel	Above	-	11.4
Channel	Below	-	10.3
Channel margin	Above	Oregon	23.8
Channel margin	Below	Oregon	13.5
Channel margin	Above	Washington	19.0
Channel margin	Below	Washington	7.1
Near shore	Above	Oregon	0.0
Near shore	Below	Oregon	10.1
Near shore	Above	Washington	0.0
Near shore	Below	Washington	4.8

5.3 Discussion

The highest densities of detected fish were at the channel margin in both spring and summer. The second highest densities were found in the channel, and the lowest densities were found near shore in all three cases. However, the hydroacoustic method used to observe fish distribution was biased against observation of fish near shore and at the surface. There were no fish detected near shore above the dredge during mobile hydroacoustic surveys in summer. This was probably due to the small sample time spent near these shores, the lack of near shore habitat due to steep banks in the river reach surveyed, and the bias against detection of fish within 2.75 m of the hydroacoustic system's transducer.

Numbers of fish detected during dredging at the outflow on the Oregon shore were significantly greater above the outflow than below. It is possible that fish were avoiding the outflow by going around it or that they held above the spoil outflow, which would explain the large numbers of fish above the outflow near shore and at the channel margin detected by the fixed transducer. The fish moved in closer to shore further downstream as shown by 10.1% of the fish being detected near shore during the mobile survey.

Because most of the data were collected at night, detecting vertical migration of fish relative to light levels was difficult. More daytime survey work is needed to calculate if vertical distribution differs between day and night.

6.0 Observations of the Behavior of Fish Relative to the Columbia River Navigation Channel and Channel Maintenance Activities in 1998[(a)]

Observations of fish distribution in the lower Columbia River near Jones Beach made during the 1998 outmigration using hydroacoustic methods indicated that the navigation channel margin is a significant habitat feature and is widely used by fish. The navigation channel margin is the sloped region leading from shallower near-shore areas to the more uniform navigation channel bottom. The observations also indicted that fish might move preferentially into navigation channel margin areas following normal diel behavior patterns or when disturbed by dredging or other activity in the navigation channel. (See Chapter 5 of this report.)

The navigation channel margin had not been identified as an important fish habitat feature in previous studies of fish distribution and behavior because of the limitations of physical capture gear historically used to sample fish. The physical capture gear used - beach seines, trawls, and purse seines for example - is typically inefficient over non-uniform bottom configurations such as that presented by the navigation channel margin.

Researchers have speculated that the historically observed decrease in net capture of migrating salmonids from the navigation channel at night might be the result of these fish seeking refuge near the bottom of the navigation channel at night. They further speculated that this behavior could increase the risk of entrainment of endangered salmonids during dredging at night.

Based on our observations of fish distribution from the 1997 study (see Chapter 5), we propose another explanation for fewer fish being observed in the navigation channel at night. We speculate that at night the proportion of fish located in the navigation channel margin area increases because of a shoreward movement of fish out of the higher velocity water in the navigation channel to regions of lower water velocity where energy expenditure to hold position during darkness is less. Our objective during 1998 was to acquire fish distribution data during daylight, evening (low light), and nighttime periods that would permit a more quantitative description of use of the navigation channel margins by fish and provide information on the occurrence of fish near the bottom of the navigation channel. A second objective was to determine if there was a diel horizontal movement of fish between the channel, channel margin, and shore, and to see if there was a change in vertical distribution.

6.1 Study Methods

Mobile hydroacoustic surveys were conducted during the summer juvenile salmon outmigration (July 14-16, 1998) to monitor vertical and horizontal fish distribution in the river. We were unable to sample the top 2.75 m of the water column because of a 2 m blanking range and because the transducer was mounted 0.75 m below the surface. Due to inability to detect fish within 1 pulse resolution volume, we were unable to detect fish within about 0.15 m of the bottom.

(a) This study was originally prepared by M.A. Weiland while with AScI Corp., T.J. Carlson while with the U.S. Army Corp pf Engineers-Portland District, and Peter Johnson of AScI Corp.

The mobile hydroacoustic system consisted of a Model 103 echosounder and a 12-degree 420-kHz split beam transducer manufactured by Precision Acoustic Systems (PAS) Incorporated of Seattle, Washington. The system was controlled by a Gateway 120-MHz pentium computer and HARP software developed by Hydroacoustic Assessments of Seattle, Washington. The transducer was pinged at 20 pings per second and had a maximum depth of 20 m. The transducer was mounted on a BioSonics Biofin and deployed from a boom off the bow of a 24-ft boat. Position was recorded using a Trimble Pathfinder Pro-XL geographical positioning system (GPS) and was linked with OMNISTAR to differentially correct and provide real-time submeter accuracy. Numbers of tracked fish were expanded for beam width to normalize for depth:

$$\text{Expansion factor} = MD / (2 * DD * (TAN(7))) \qquad \text{[Eq. 6.1]}$$

Where:
MD is the maximum diameter of the beam,
DD is the beam diameter at the fish distance from the transducer,
TAN is the tangent, and
7 is the effective beam half angle.

The maximum effective beam angle for the transducers was estimated to be 14 degrees. Data was manually tracked using a Visual Basic tracking program developed by the Portland District CE (Bill Nagy, Fishery Field Unit, Bonneville Dam, Portland District, US Army Corps of Engineers). The data were then analyzed using SAS (Statistical Analysis System).

Data were collected from the lower Columbia River below Westport Slough to Welch Island (Figure 6.1). The river was divided into three habitat types for analysis: navigation channel, channel margin, and inshore. The navigation channel was characterized as the deep-water region, usually greater than 15 m, with a rather uniform bottom. The channel margin was a sloping region with a noticeable gradient leading from the channel up to the inshore area. The inshore region was characterized as a shallow area near the bank, or points, where the water was normally less than 7 m deep. All depths for this report are reported as distance from the bottom of the river.

6.2 Results

6.2.1 Horizontal Distribution

Significantly more fish were detected in the channel (42.2%) and channel margin (40.4%) than were detected nearshore (17.4%) ($P<0.05$). During evening and nighttime, greater densities of fish were detected in the channel and channel margin than inshore (Figure 6.2). Densities differed between evening and night. In the evening, 14.2% were found nearshore, 49.8% were in the channel margin, and 36.0% were in the channel. At night 8.2% were found nearshore, 42.9% were in the channel margin, and 48.9% were in the channel. During the day, however, more fish were detected nearshore (40.2%) than in the channel (26.2%) or channel margin (33.6%). The percent of fish utilizing each of the three habitats during the day, evening, and night varied over the three dates sampled (Figure 6.3a-c). In the evening, the proportion varied from 0-19.2% nearshore, 39.7-60.7% at the channel margin, and 20.1-60.3% in the channel. At night the proportion varied from 0-25.8% inshore, 25.8-50.3% at the channel margin, and 37.5-57.5% in the channel. Though proportions of fish varied, the trend shows most of the fish utilizing the channel and channel margin during the evening and night.

6.2.2 Vertical Distribution

There was a significant difference in vertical distribution of detected fish during daytime, evening, and nighttime hours ($P<0.05$) in the channel and channel margin. A significant difference in vertical distribution was not found for fish inshore ($P>0.05$) (Figure 6.4a). At the channel margin, fish were significantly closer to the bottom during the evening and night (1900-2100 and 2200-0200, respectively) ($X=4.6$ m and 4.2 m, respectively) (Figure 6.4b), and were farthest from the bottom during day sampling (1300-1500) ($X= 6.1$ m). In the channel, fish were significantly higher in the water column during the day and night ($X=9.9$ m and $X=8.5$ m, respectively) and were found deeper in the evening ($X=6.9$ m) (Figure 6.4c).

Most fish in the inshore habitat were detected within 2 m of the bottom (Figure 6.5a). At the channel margin, the highest densities of the fish were detected between 3 and 10 m from the bottom (Figure 6.5b). In the channel, the highest densities of the fish were detected between 5 and 15 m from the bottom (Figure 6.5c).

6.2.3 Risk of Entrainment

The region of influence where fish could be entrained by the suction head from the dredge is within 1 m of the bottom. About 3.2% of the fish were detected within this 1-m zone (Figure 6.4a-c). The percent of fish utilizing this 1-m region varied with time. About 0.37% of fish were detected in this region during the day, 4.98% in the evening, and 2.14% at night. This percentage represents fish distributed across the width of the entire navigation channel in the bottom meter, where the suction head at any time only influences a small portion of the channel, about 1/200th. Calculated for possible entrainment by the suction head, about 0.0160% of fish could be entrained by the dredge. About 0.0017% of fish would be in the immediate vicinity of the suction head during the day, about 0.0249% in the evening, and 0.0107% at night. This is similar to the night estimates in 1997 of 0.01 and 0.009%.

This rough estimate of dredge entrainment risk is believed to be conservative, particularly for subyearling chinook, because of the documented near shore distribution of subyearling chinook (Dawley et al. 1985 a and b) and our inability to sample water shallower than 2.75 m with the hydroacoustic gear deployment methods used for the fish distribution surveys. The hydroacoustic gear deployments we used biased our detected fish distribution estimates against fish located near shore or near surface where the majority of subyearling salmonids are believed to occur (Dawley et al. 1985 a and b). The distribution of subyearling chinook in particular would place them well away from the suction head of a dredge, which is almost always located within the navigation channel boundaries.

6.3 Discussion

The objective of this study was to acquire fish distribution data during daytime, evening, and nighttime periods to better estimate the vertical movement of fish and to estimate differences in distribution within the volume sampled. Higher densities of fish were detected in the channel in 1998 than were detected in spring or summer 1997 (Table 6.1). This difference is possibly due to higher flow levels in 1997, which caused fish to seek refuge in the lower flows of the channel margins. We found differences in habitat use during different time periods. Significantly higher densities of fish were detected in the channel and channel margin during the evening and at night, but densities were higher near shore during the day. Vertical fish distribution also differed significantly between time of day in the channel and channel margin, but not near shore. Fish were significantly closer to the bottom during the evening and night at the channel margin and farther from the bottom during the day. In the channel, fish were significantly closer to the bottom during evening and were higher in the water column during the day and night. Our observations do not agree with the speculation that fish are moving into and holding (or occur in higher density) near the bottom of the navigation channel at night.

The region of influence where fish could be entrained by the suction head from the dredge is within 1 m of the bottom. About 3.2% of the fish were detected within this 1-m zone. This percentage varied with 0.37% of all fish detected in the 1-m zone during the day, 4.98% in the evening, and 2.14% at night. Taking in to account the size of the suction head, about 0.0160% of fish are possibly in close proximity to the suction head at any one time. About 0.0017% of fish would be in the immediate vicinity of the suction head and vulnerable to entrainment during the day, about 0.0249% in the evening, and 0.0107% at night. This estimate may be high since fish in the upper 2.75 m of the water column were not detectable and mid-water trawl catches of juvenile fall chinook salmon at Jones Beach showed 96.3% of the fish were captured within 3 m of the surface (Dawley et al. 1985 a and b). In addition, while the majority of fish occurring in the Jones Beach reach during peak outmigration periods are believed to be juvenile salmonids (Dawley et al. 1985 a and b) a portion of the fish detected hydroacoustically were likely not salmonids.

Table 6.1. Percent of Fish Detected during each Study Period in the Inshore, Channel Margin, and Channel Habitats

	Inshore	**Channel Margin**	**Channel**
Spring 1997	15.3	55.5	29.2
Summer 1997 (downstream site)	26.2	42.1	31.7
Summer 1997 (upstream site)	15.0	63.3	21.7
Summer 1998	17.4	40.4	42.2

7.0 References

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Figures

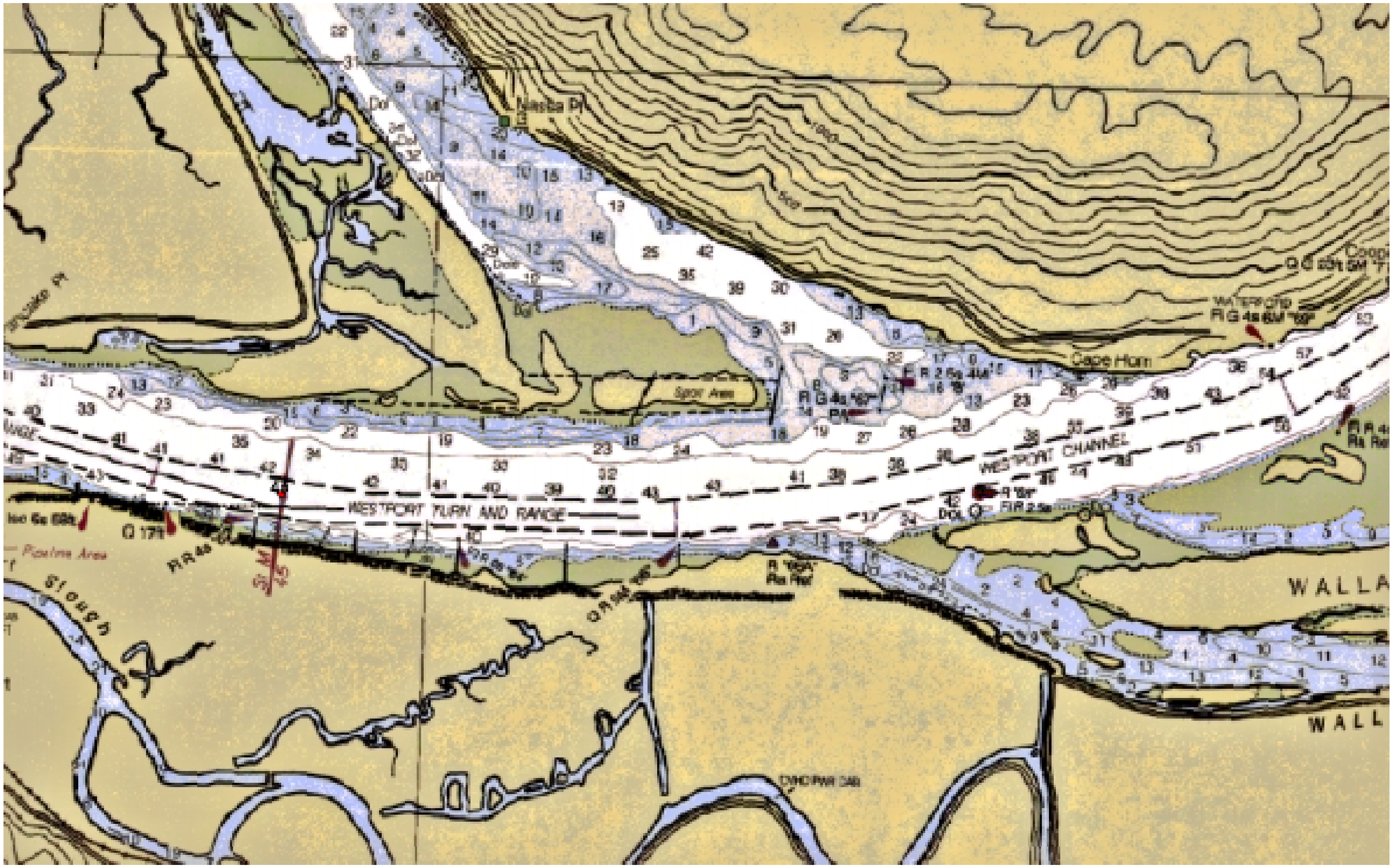

Figure 2.1. Bathymetry of the Jones Beach Reach Located at Approximately River Mile 45 on the Lower Columbia River. The red dot mid-channel marks river mile 45 as measured from the mouth of the Columbia River.

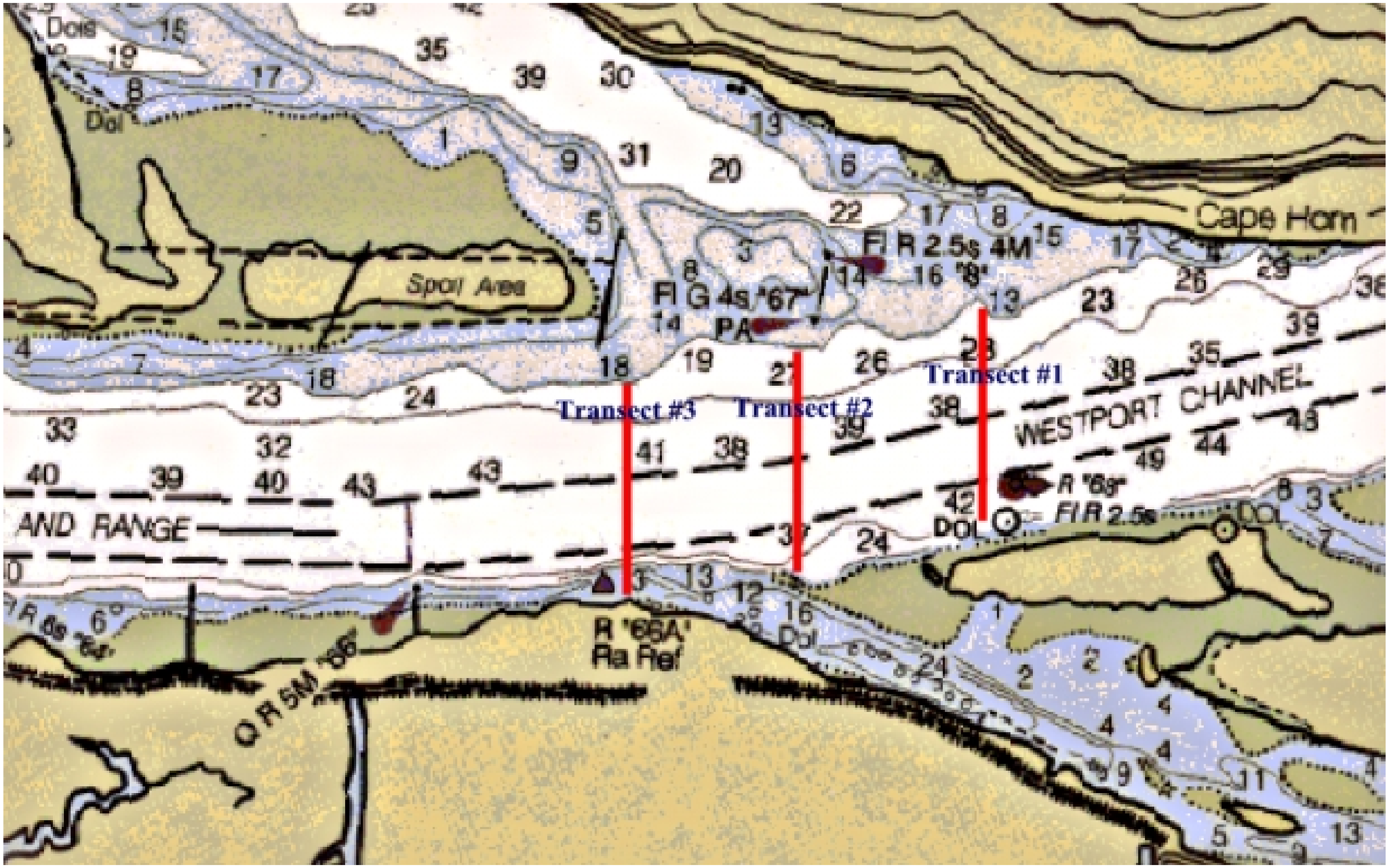

Figure 2.2. Jones Beach Reach Showing Location of Sampling Transects Near Operating Dredge

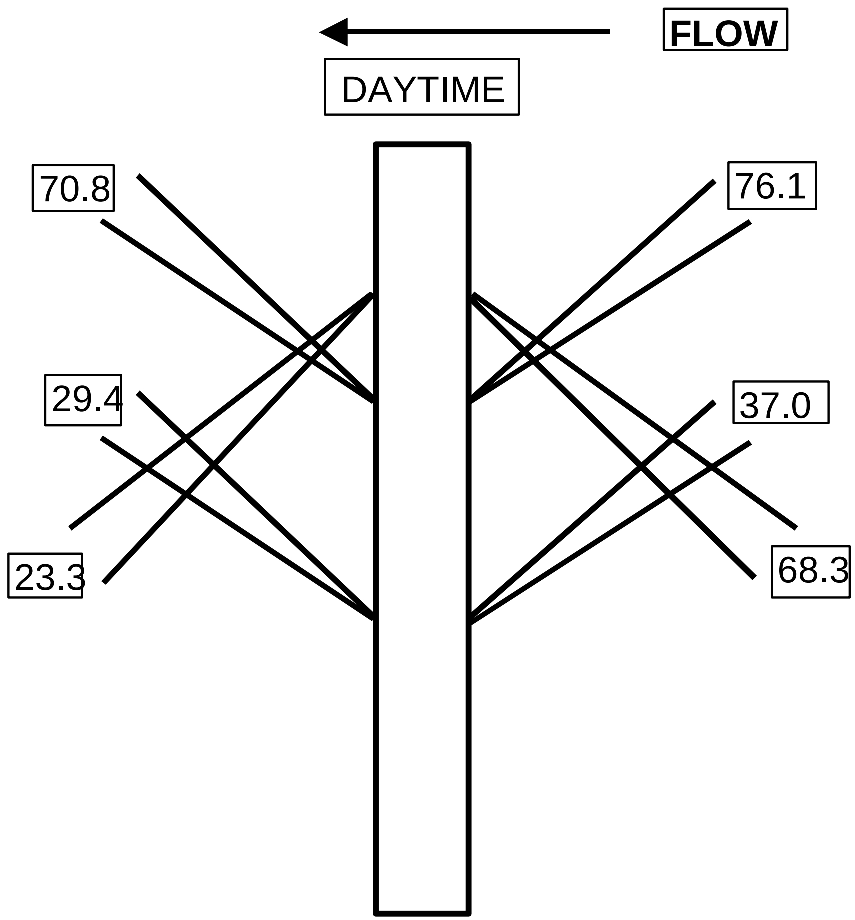

Figure 3.1. Schematic Showing the Net Movement of Fish Observed during the Day in the Immediate Vicinity of a Pile Dike Located at Jones Beach (river mile≈ 45) on the Lower Columbia River. Positive numbers indicate movement in the direction of river flow. The center rectangle represents the pile dike oriented orthogonal to the shore. The base of the rectangle is positioned on the shore.

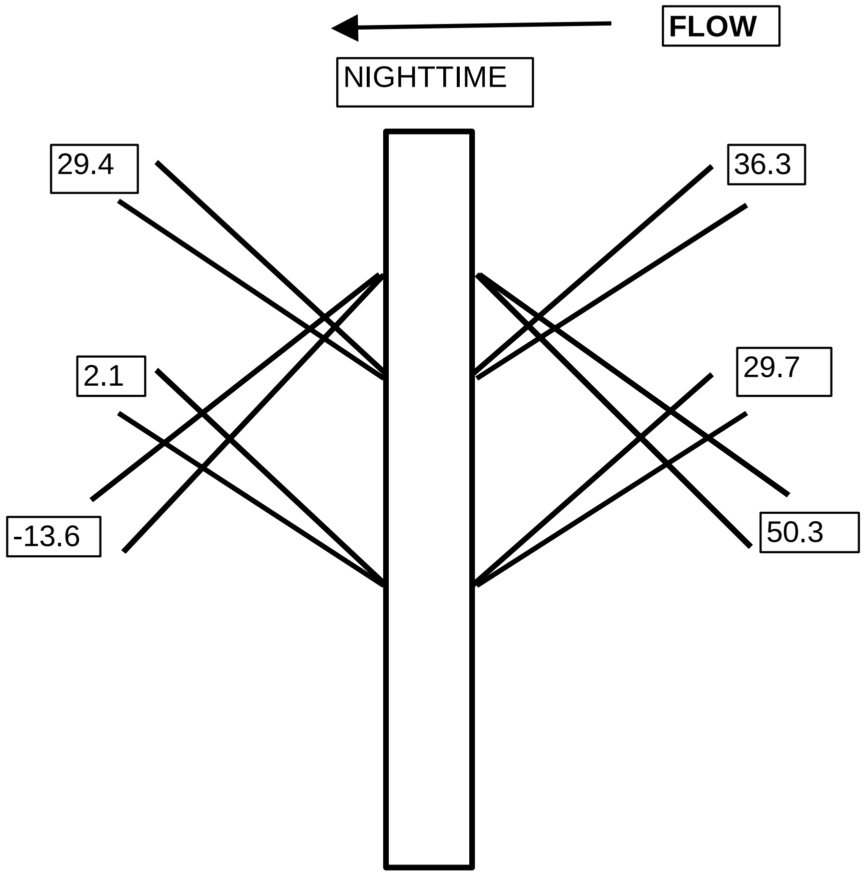

Figure 3.2. Schematic Showing the Net Movement of Fish Observed during the Night in the Immediate Vicinity of a Pile Dike Located at Jones Beach (river mile ≈ 45) on the Lower Columbia River. Positive numbers indicate movement in the direction of river flow. The center rectangle represents the pile dike oriented orthogonal to the shore. The base of the rectangle is positioned on the shore.

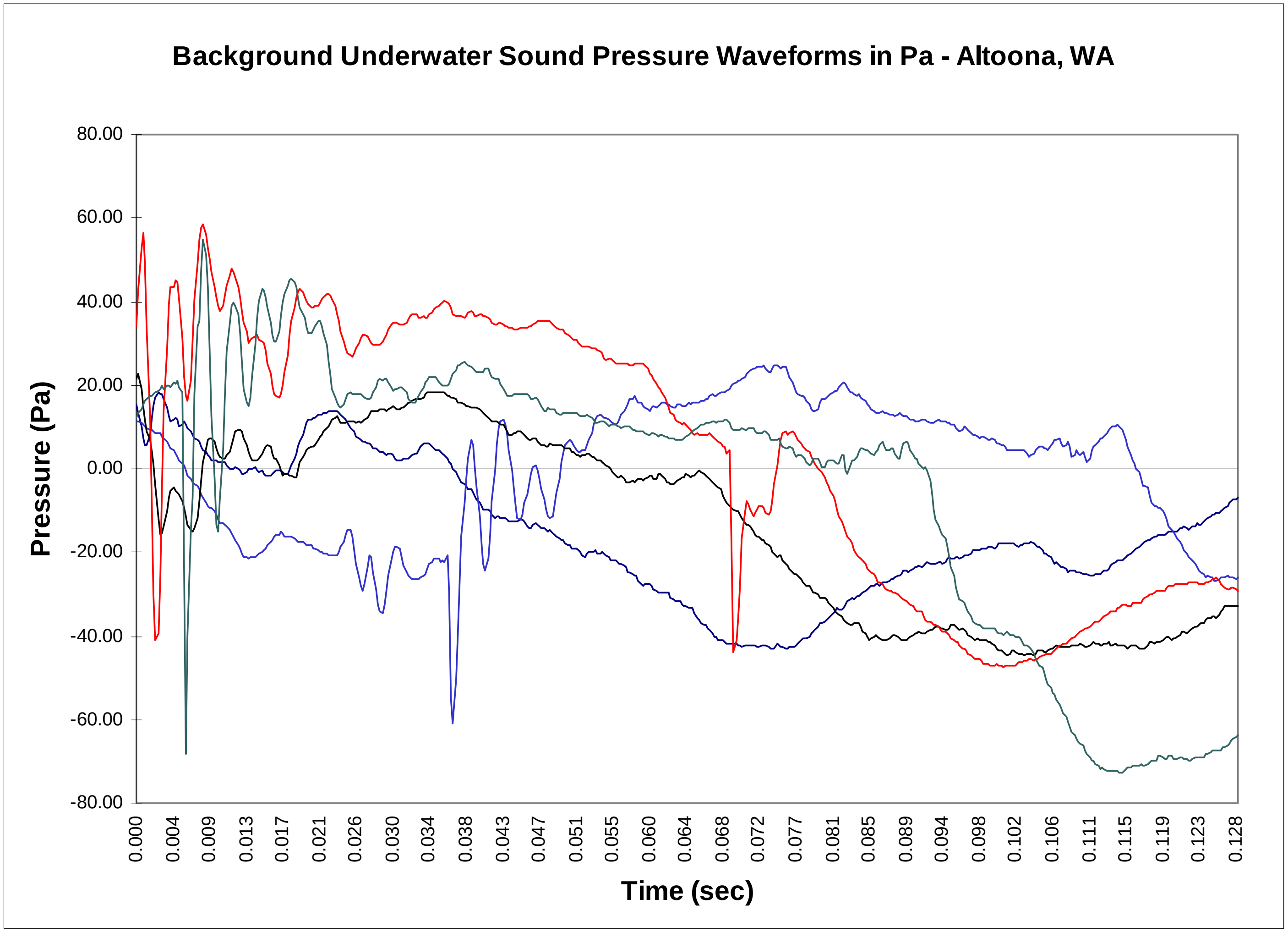

Figure 4.1. Samples of Background Underwater Sound Time Domain Signals. The signals consist of a low-frequency wave resulting from wave action, modulated by sound present when the signals were recorded.

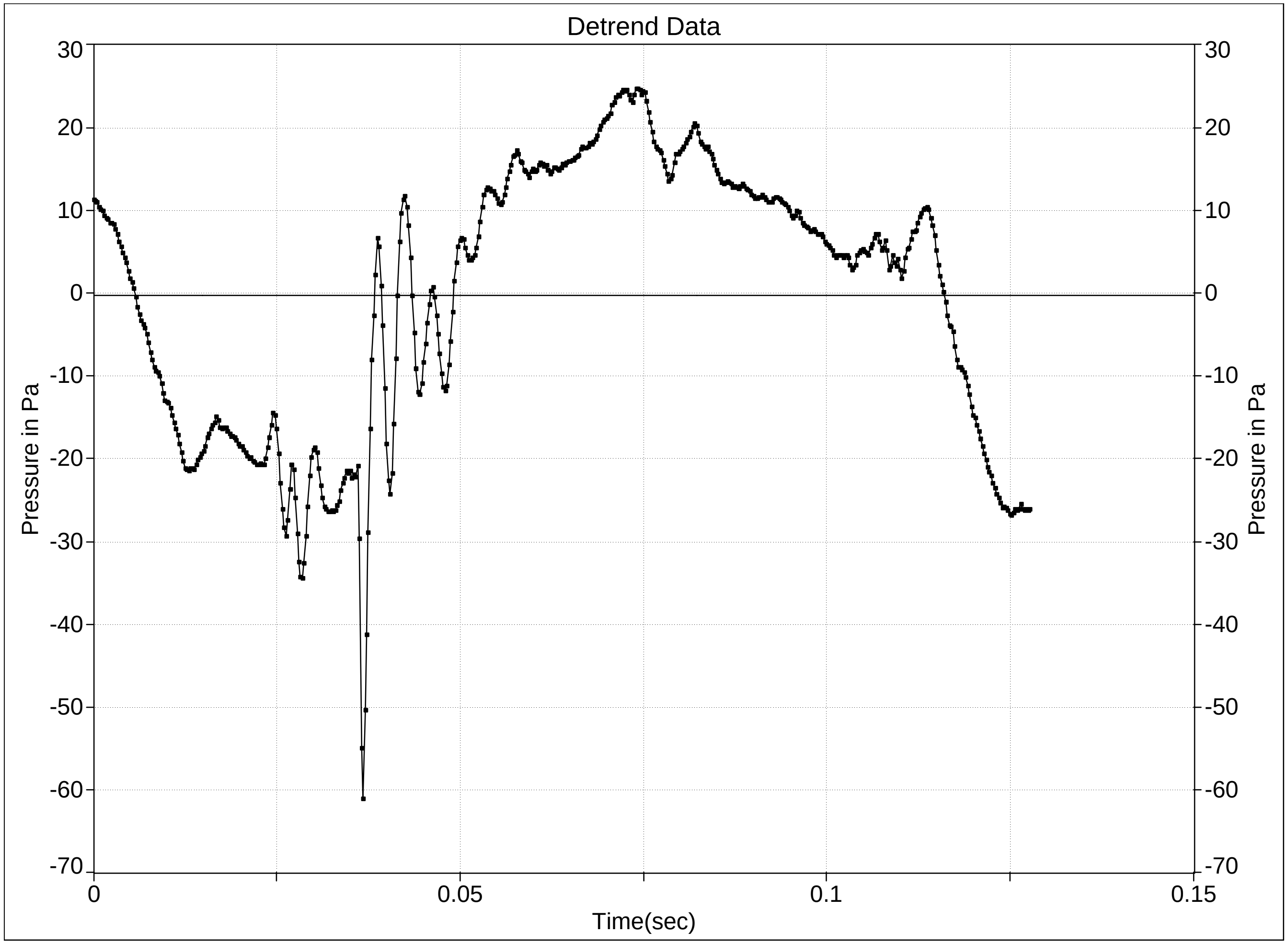

Figure 4.2. Time Domain Background Underwater Sound Signal Corresponding to the Frequency Spectrum shown in Figure 4.1. The low frequency wave that is a major feature of the pressure signal is due to small waves that were present when the signals were recorded. The higher frequency modulation of this low-frequency wave is the "sound" present at the instant when the signal was recorded.

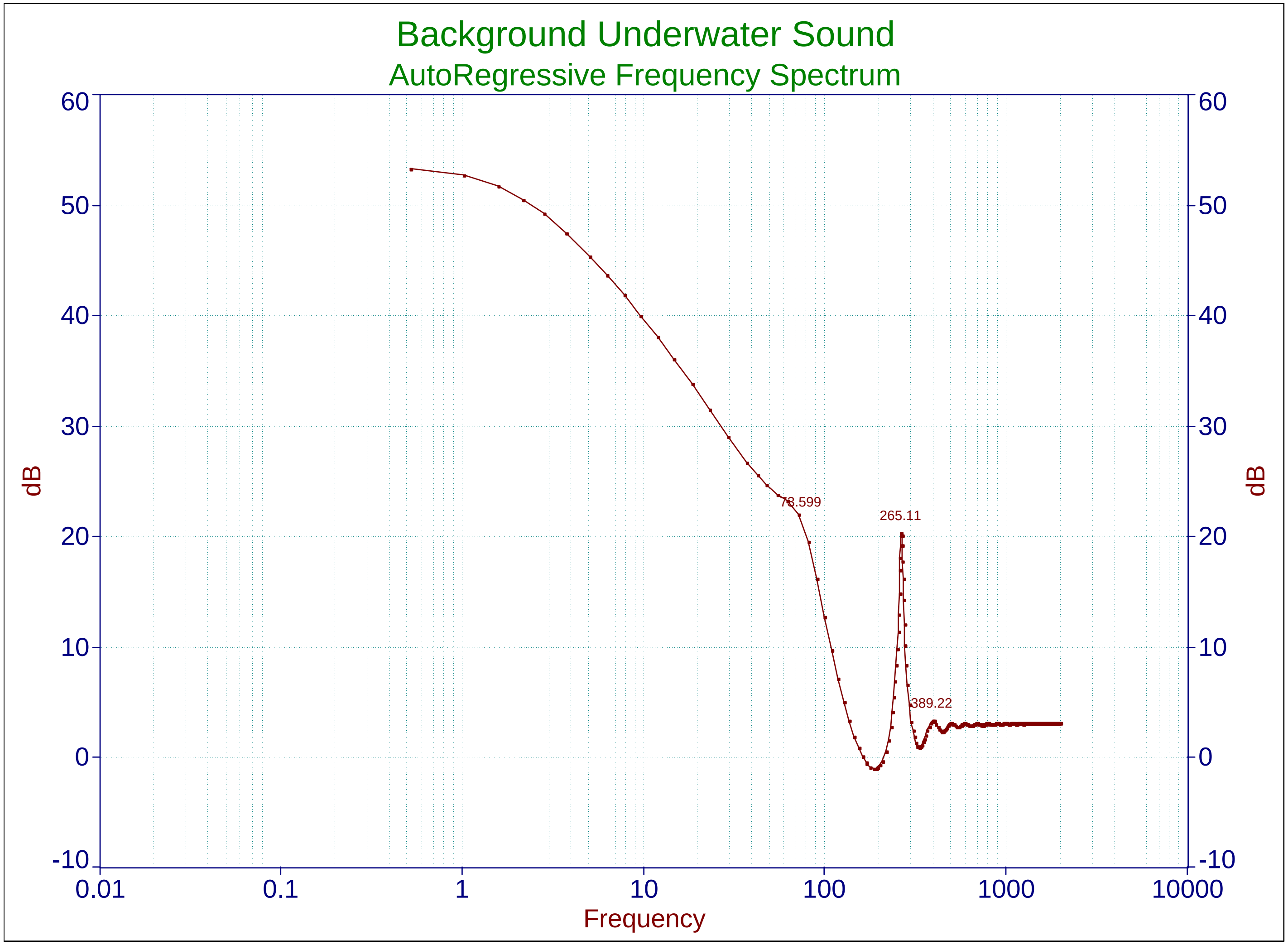

Figure 4.3. Frequency Spectrum Corresponding to Time Domain Sample of Background Underwater Sound Shown in Figure 4.2. Shows that the background underwater sound is mostly composed of low frequencies with a higher energy peak at about 265 Hz. The source of the higher energy peak is unknown.

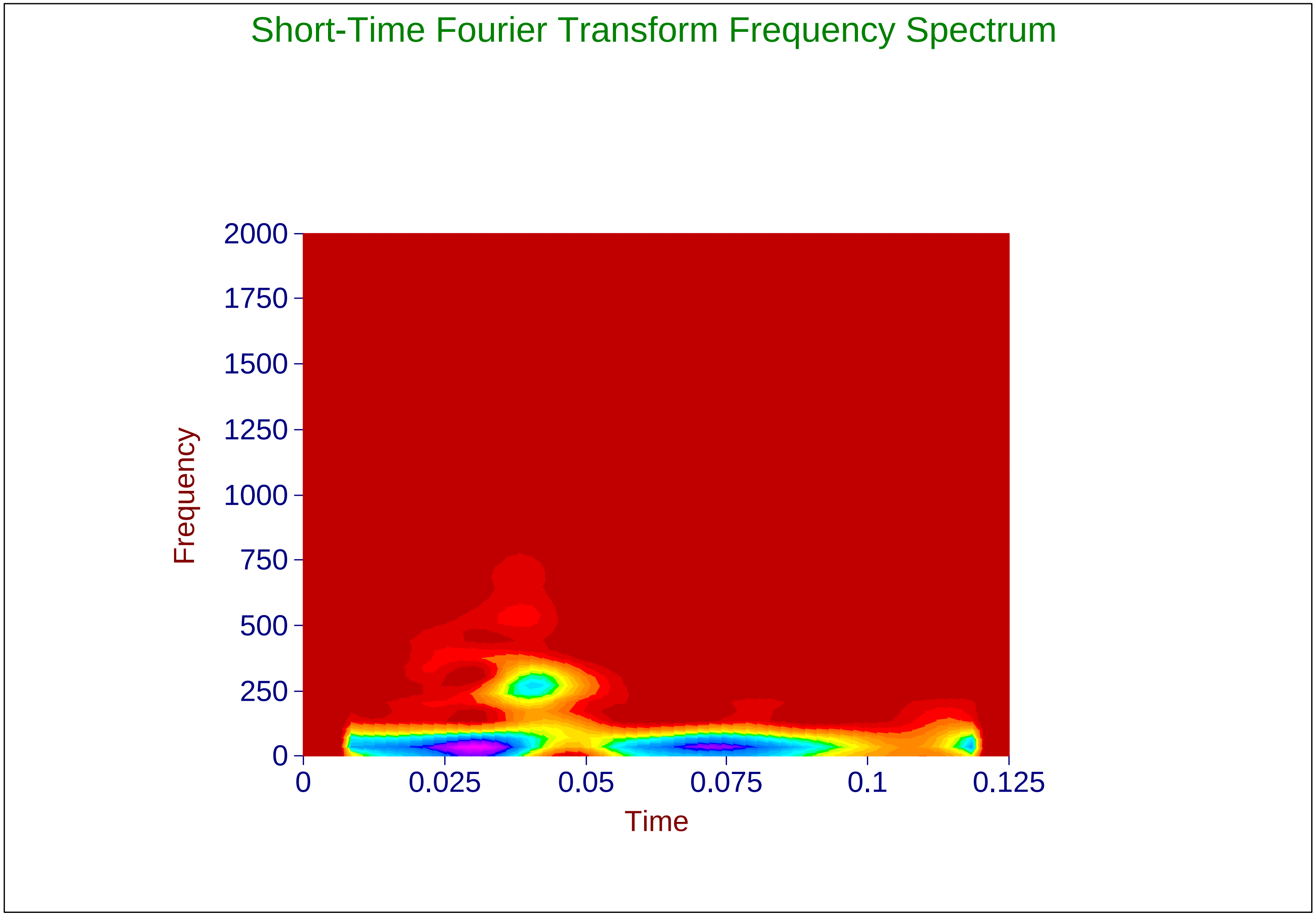

Figure 4.4. Time-Frequency Contour Plot Corresponding to Background Underwater Sound Shown in Figure 4.2. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude.

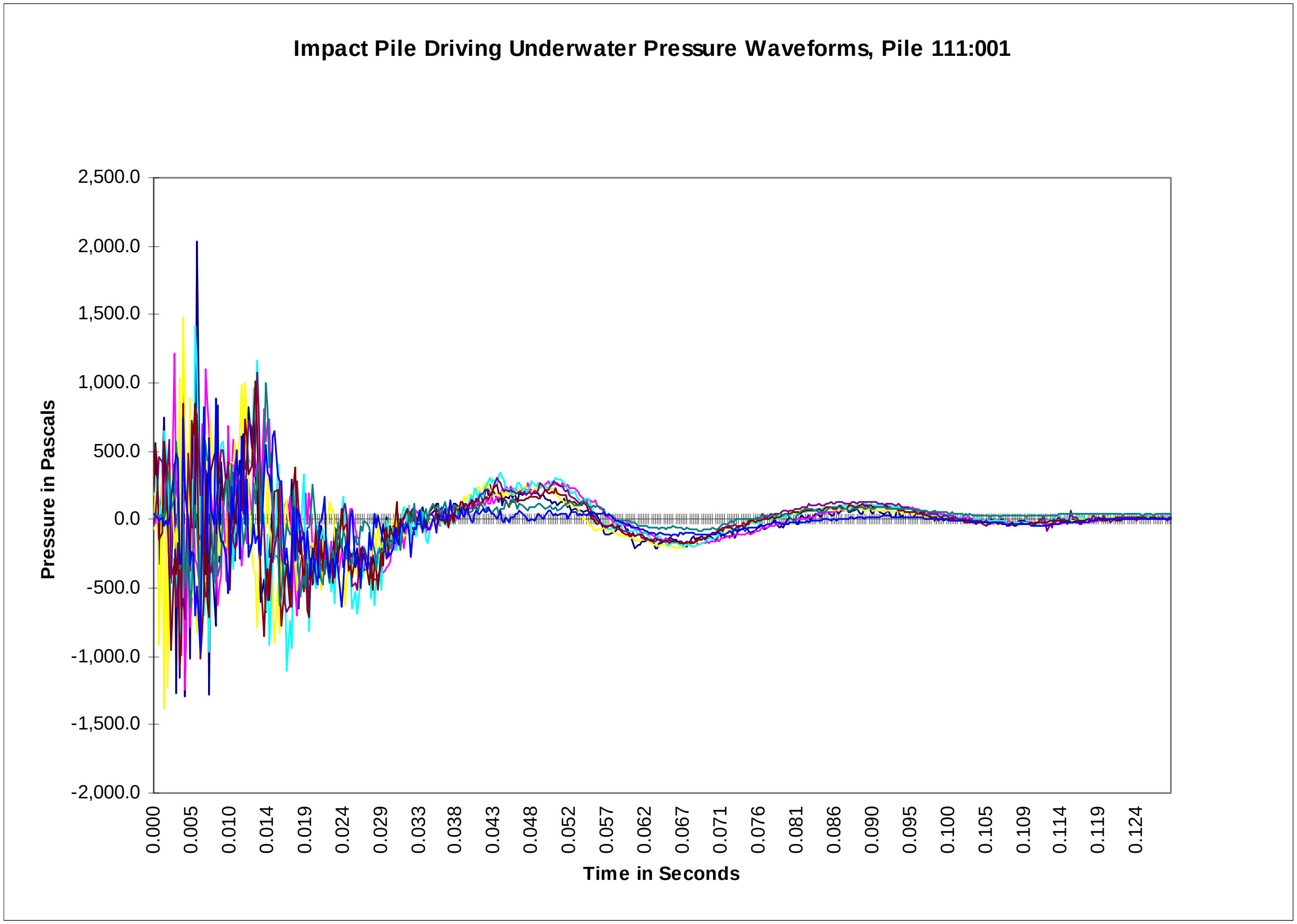

Figure 4.5. Samples of Underwater Sound Signals from Several Pile Driver Strikes Recorded During the Driving of Pile 111:001.

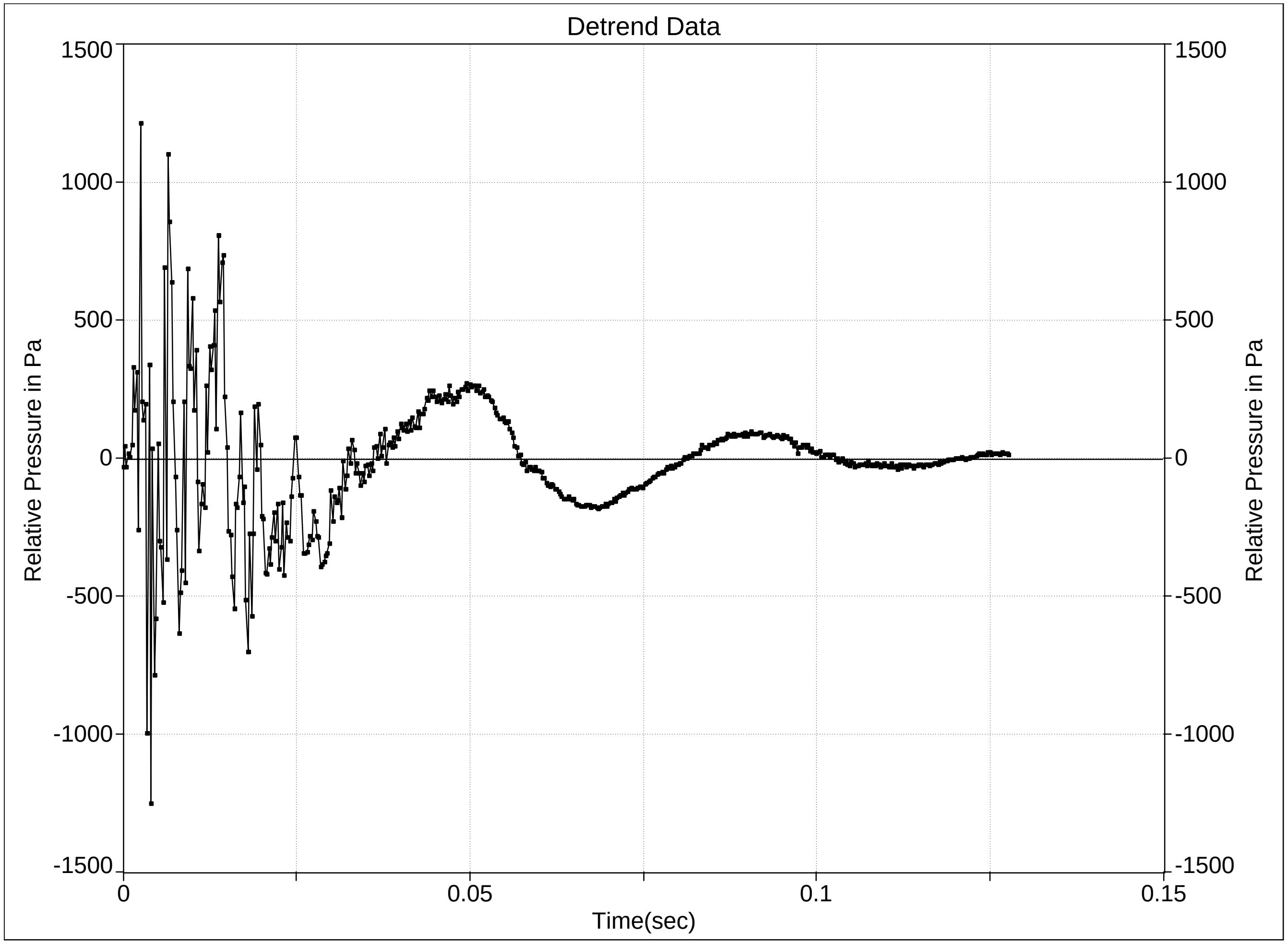

Figure 4.6. Underwater Sound Time Domain Signal Resulting from One of the Strikes Observed during Driving of Pile 111:001. This signal is one of those shown in Figure 4.5. The signal is characterized by higher amplitude immediately following the strike followed by a lower frequency oscillation, which is mostly damped out within 0.1 sec of the pile driver strike.

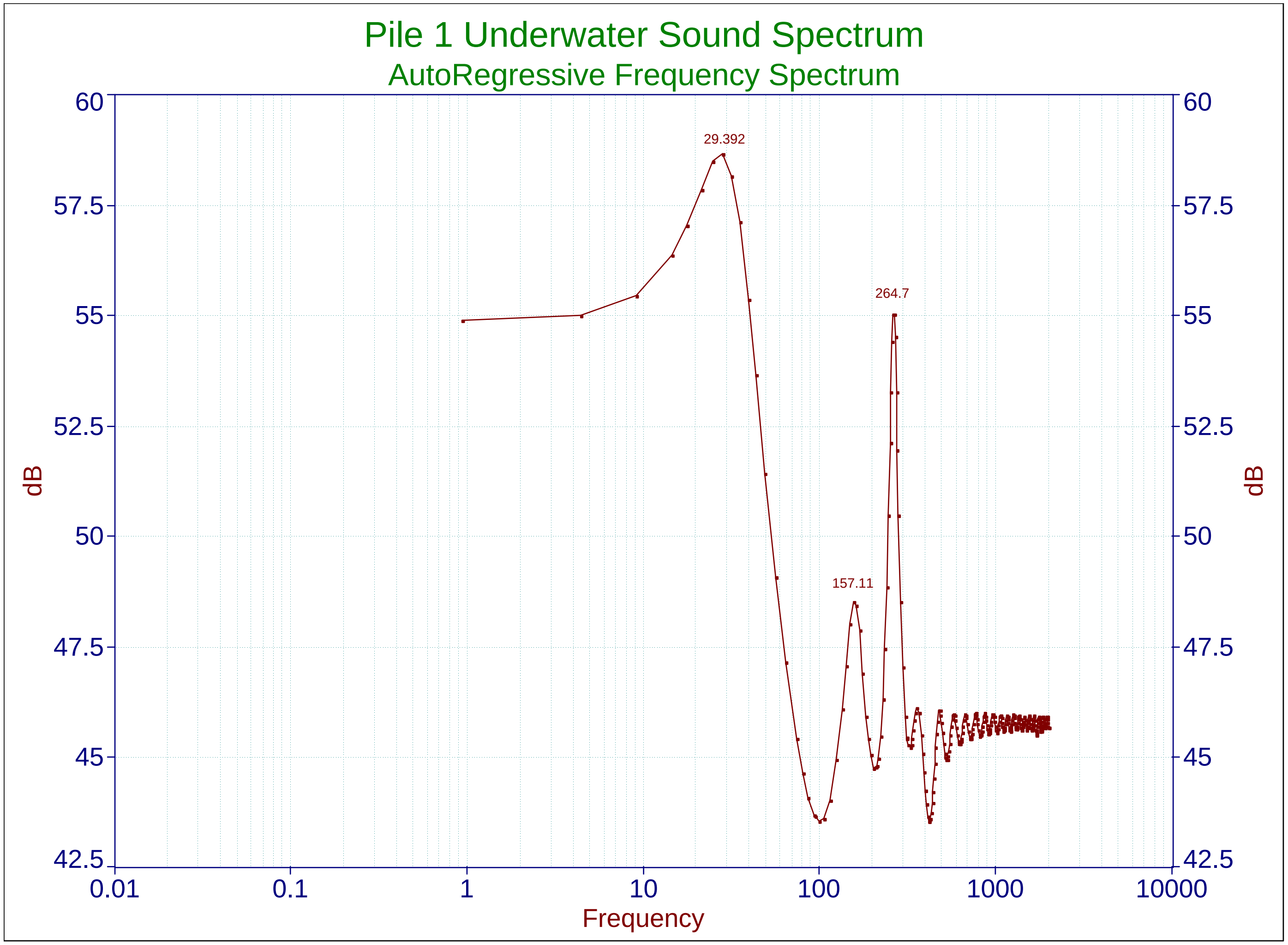

Figure 4.7. Frequency Spectrum Corresponding to Time Domain Sample of Underwater Sound Generated by the Pile Driver Strike Shown in Figure 4.6. The spectrum shows peaks at 29.4, 157.1, and 264.7 Hz. The sound at approximately 30 Hz is within the region observed to elicit avoidance response from salmonids. The level of sound at this frequency is also well above the background levels shown in Figure 4.6.

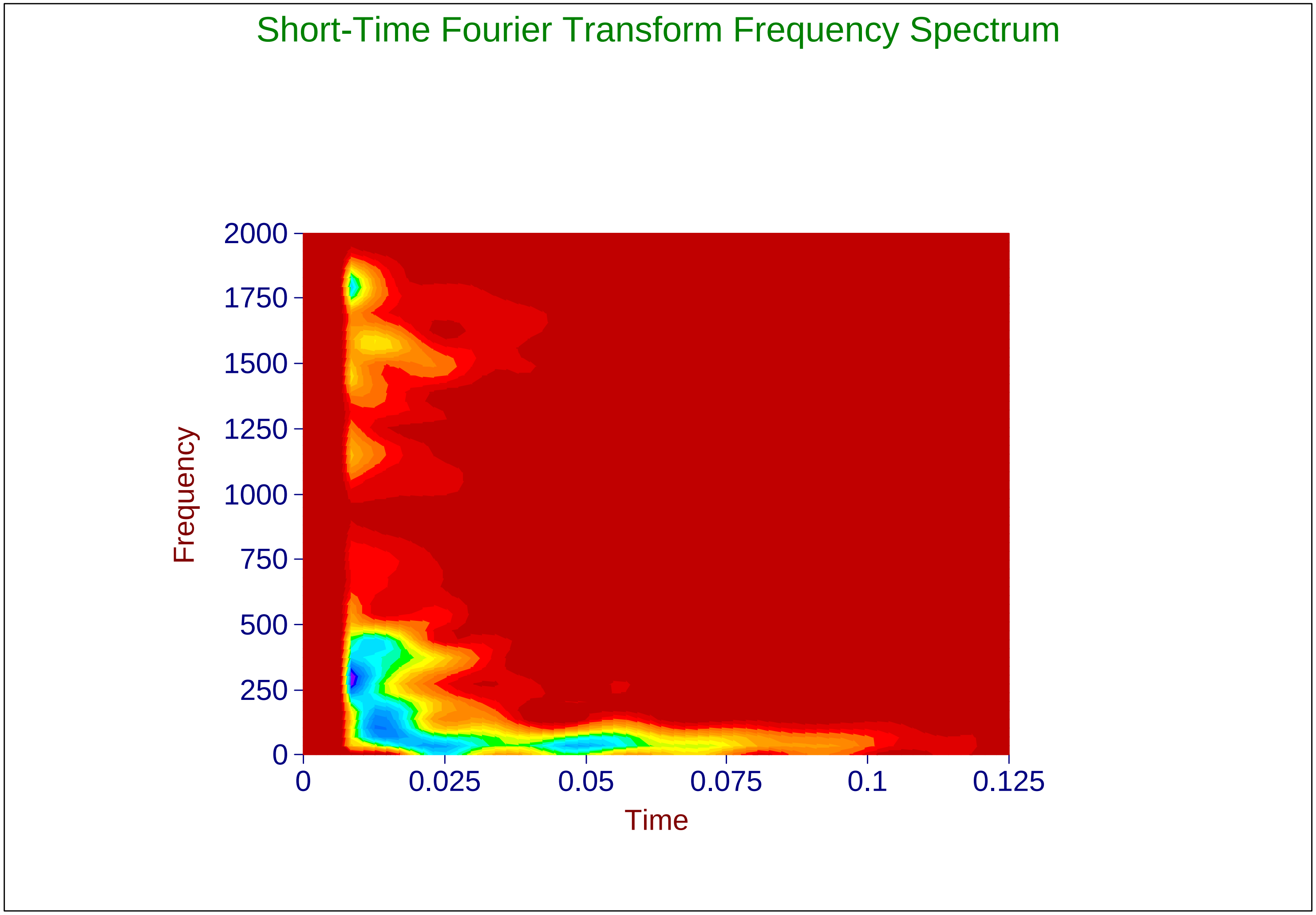

Figure 4.8. Time-Frequency Contour Plot Corresponding to the Pile Strike Shown in Figure 4.6. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude. All higher frequency components are limited to the first 0.025 sec following the strike by the pile driver. Almost all of the sound generated by the strike is gone within 0.1 sec of the pile driver strike.

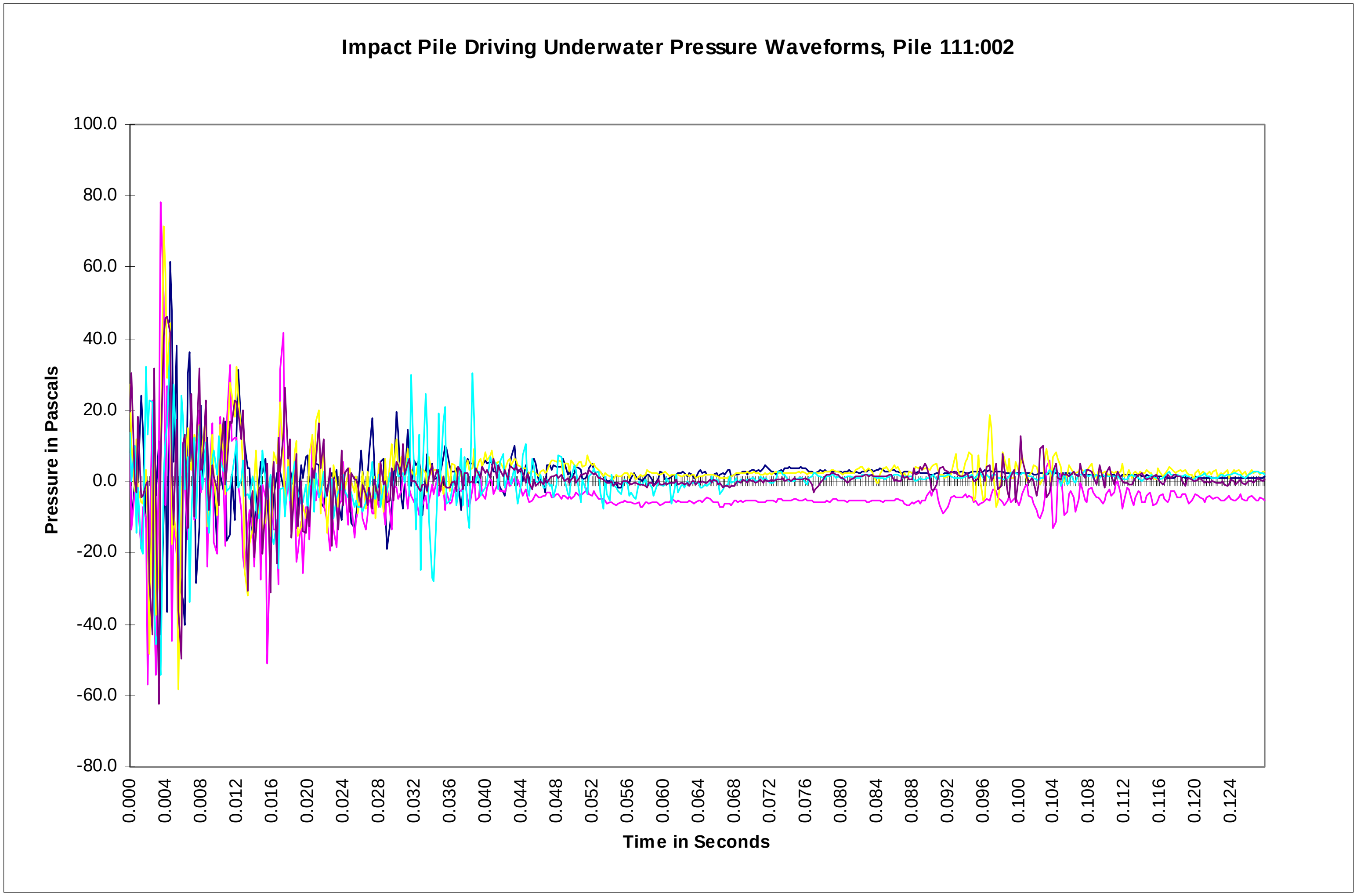

Figure 4.9. Time Domain Samples of Underwater Sound Signals from Several Pile Driver Strikes Recorded during Driving of Pile 111:002. This signal is characterized by a relatively long initial pulse of higher frequency sound followed by a second short burst of higher frequency sound generated when the pile rebounded following initial impact and hit the pile driver head as it was being raised in preparation for the next strike.

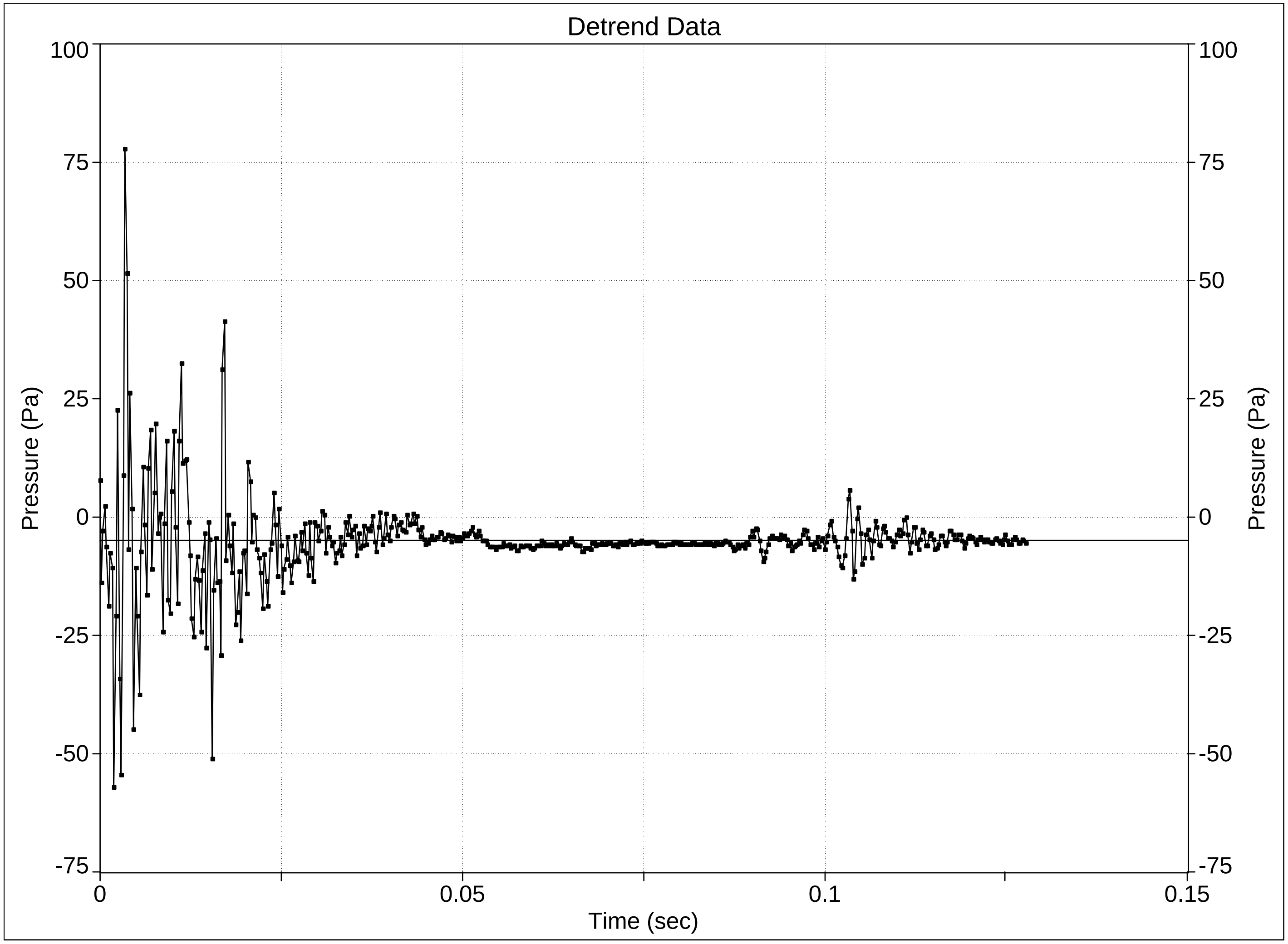

Figure 4.10. Underwater Sound Time Domain Signal Resulting from One of the Strikes Observed during Driving of Pile 111:002. This signal is one of those shown in Figure 4.9. The first segment of this signal is similar to that shown in Figure 4.9 but differs thereafter in that it does not show the low frequency wave following the initial strike and, in addition, it shows a secondary strike of the pile driver by the pile.

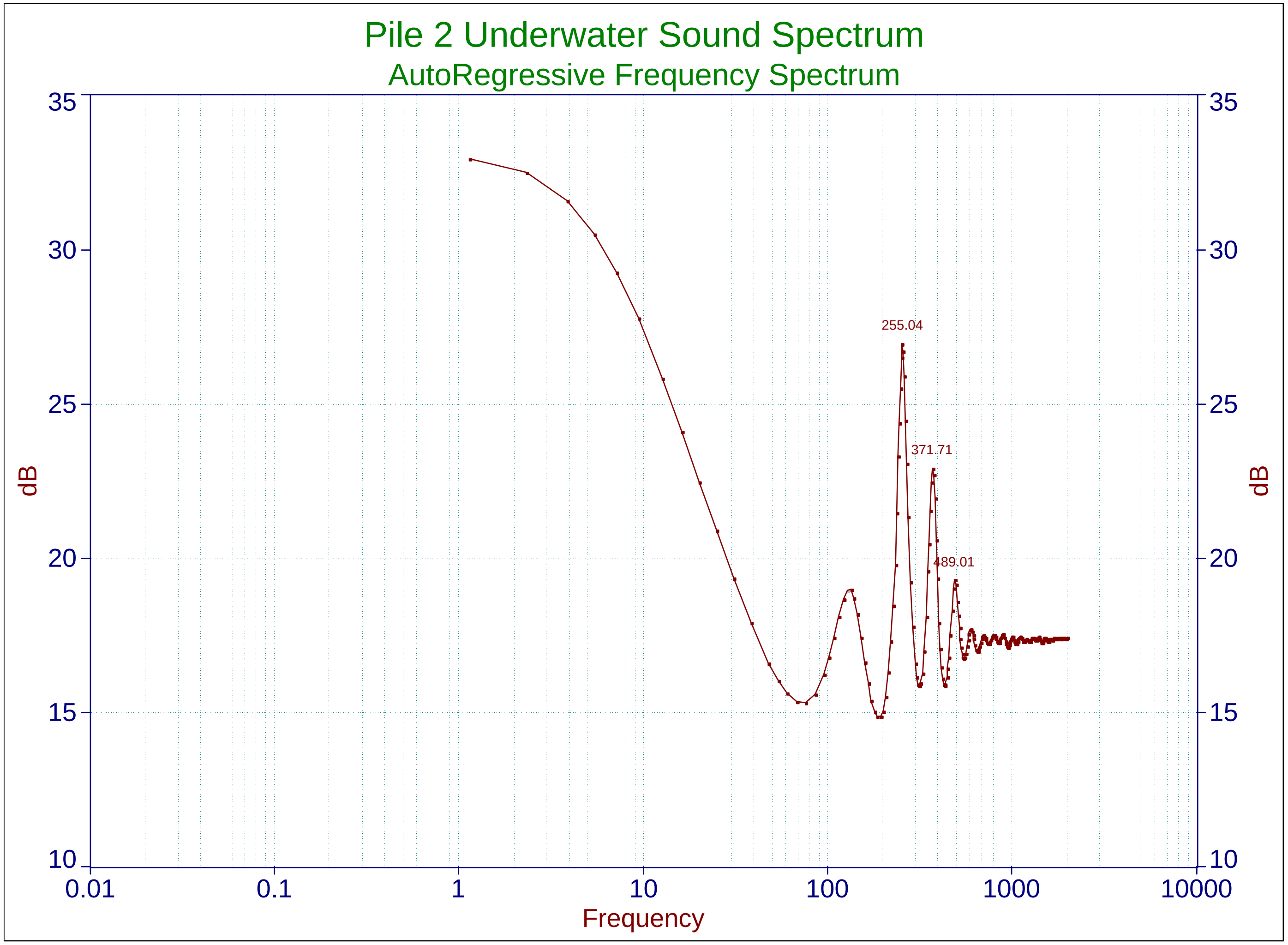

Figure 4.11. Frequency Spectrum Corresponding to Time Domain Sample of Underwater Sound Generated by the Pile Driver Strike shown in Figure 4.10. The spectrum shows peaks at≈ 150, 255, 371.7, and 489 Hz. All of the peaks shown in the spectrum, with the exception of the one at 150 Hz, are above the threshold of hearing for juvenile salmonids. The levels of these frequency components are considerably above observed background levels.

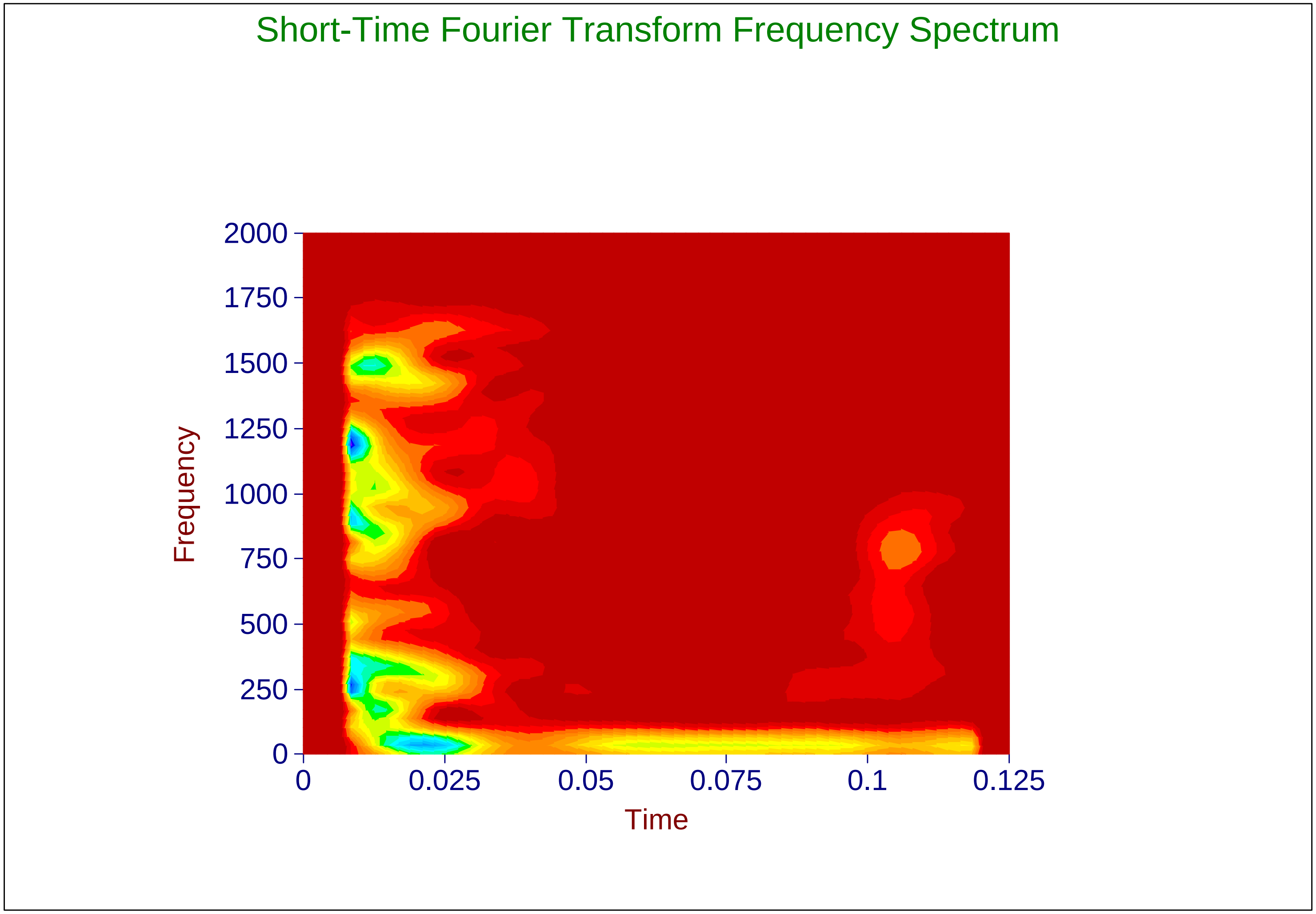

Figure 4.12. Time-Frequency Contour Plot Corresponding to the Pile Strike shown in Figure 4.10. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude. While most of the higher frequency components are limited to the first 0.025 sec, there is a second occurrence of higher frequencies resulting from the pile rebounding and hitting the pile driver. Almost all of the sound generated by the strike is gone within 0.1 sec of the pile driver strike.

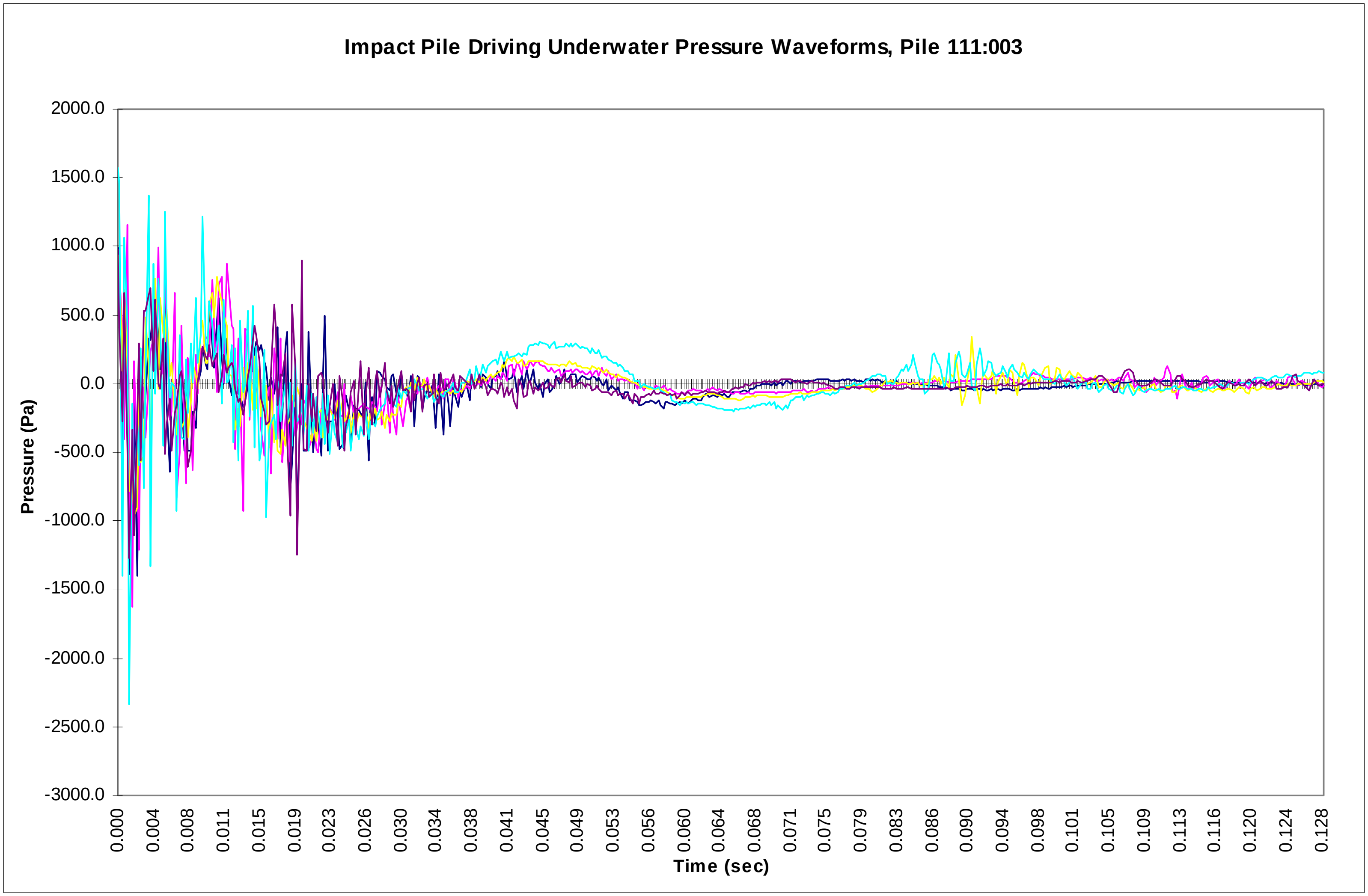

Figure 4.13. Time Domain Samples of Underwater Sound Signals from Several Pile Driver Strikes Recorded during Driving of Pile 111:003. This signal is characterized by a relatively long initial pulse of higher frequency sound followed by a low frequency waveform and a second short burst of higher frequency sound generated when the pile rebounded following initial impact and hit the pile driver head as it was being raised in preparation for the next strike.

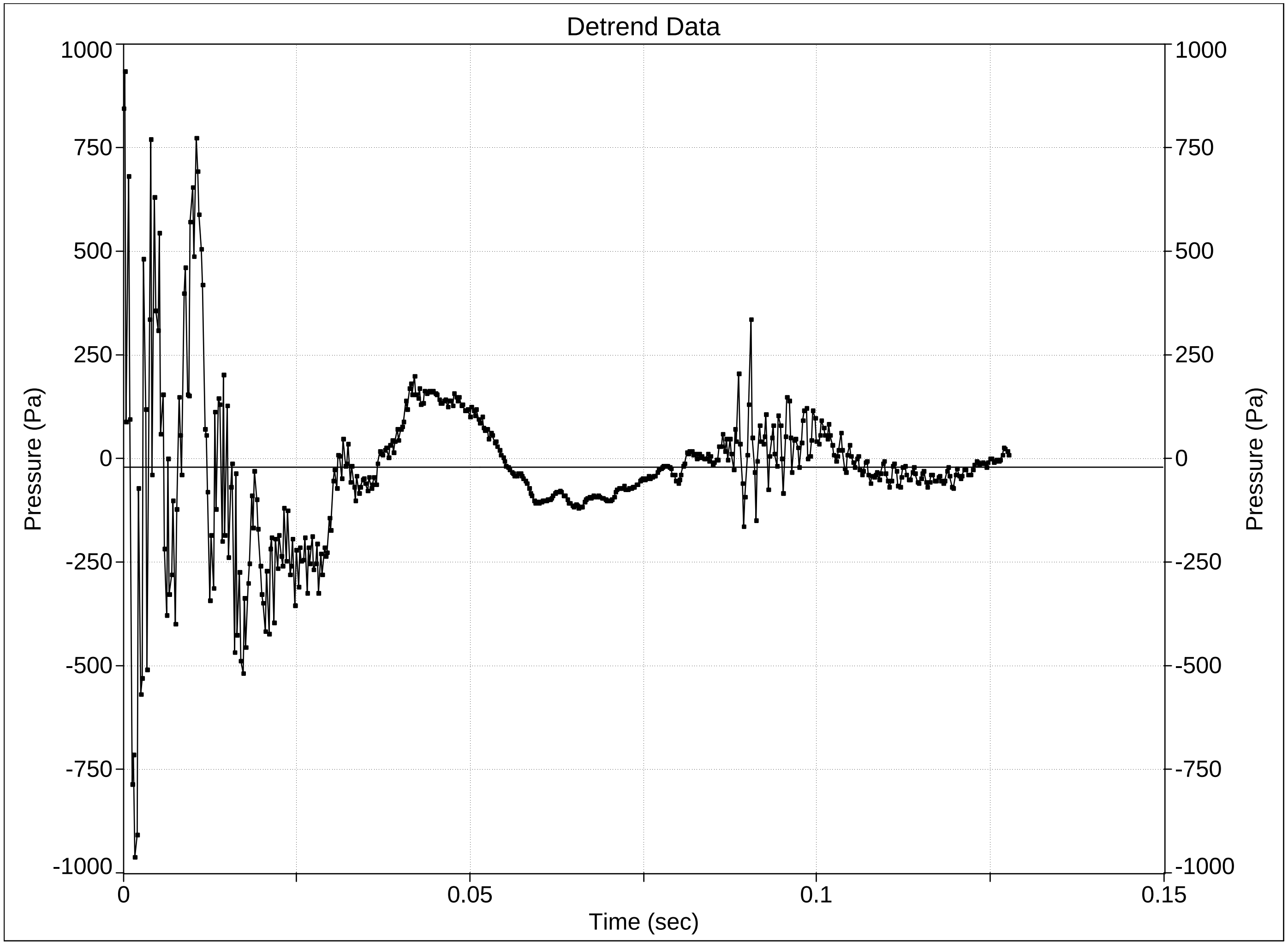

Figure 4.14. Underwater Sound Time Domain Signal Resulting from One of the Strikes Observed during Driving of Pile 111:003. This signal is one of those shown in Figure 4.13. This signal includes a combination of the features seen in the signals from the first two piles. These features include an initial high frequency burst due to initial impact then a low frequency waveform followed by a second higher frequency burst.

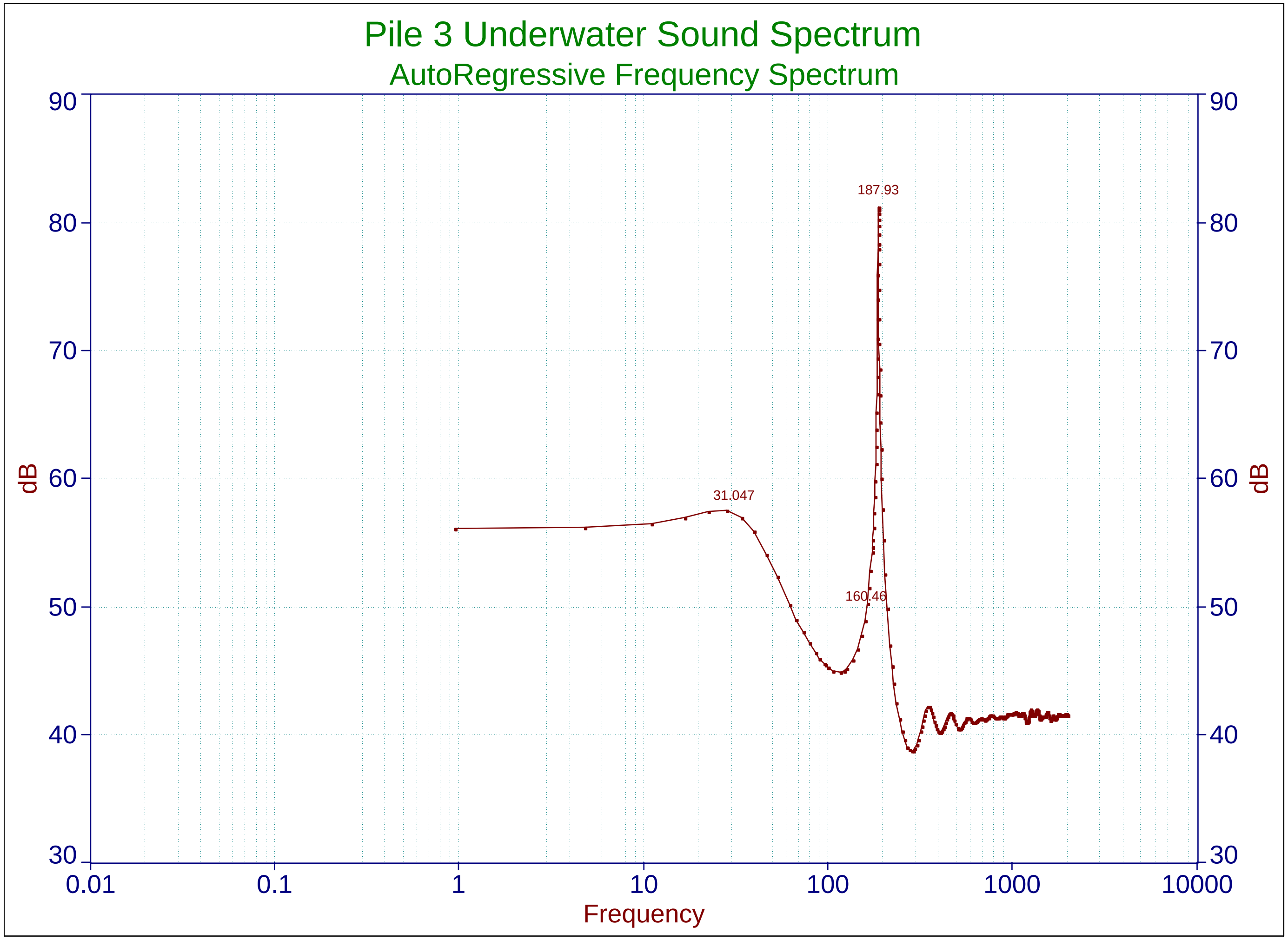

Figure 4.15. Frequency Spectrum Corresponding to Time Domain Sample of Underwater Sound Generated by the Pile Driver Strike Shown in Figure 4.14. The spectrum shows peaks at 31 and 187.9 Hz. The first peak at approximately 31 Hz is within the frequency range know to elicit avoidance responses from juvenile salmonids. The second peak at 187 Hz is above the upper hearing threshold for salmonids. The levels of these frequency components are considerably above observed background levels.

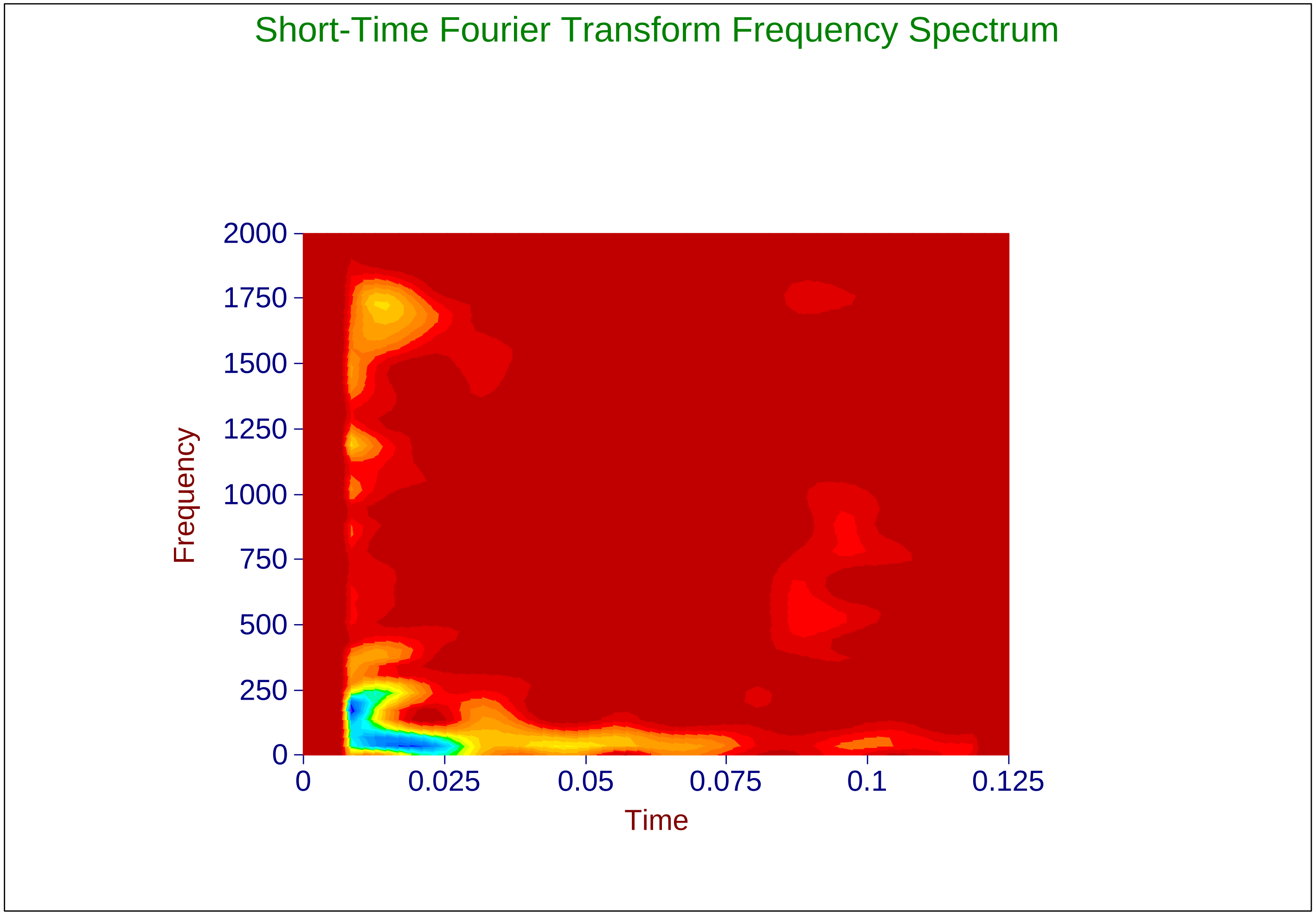

Figure 4.16. Time-Frequency Contour Plot Corresponding to the Pile Strike Shown in Figure 4.14. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude. While most of the higher frequency components are limited to the first 0.025 sec, there is a second occurrence of higher frequencies resulting from the pile rebounding and hitting the pile driver. Almost all of the sound generated by the strike is gone within 0.1 sec of the pile driver strike.

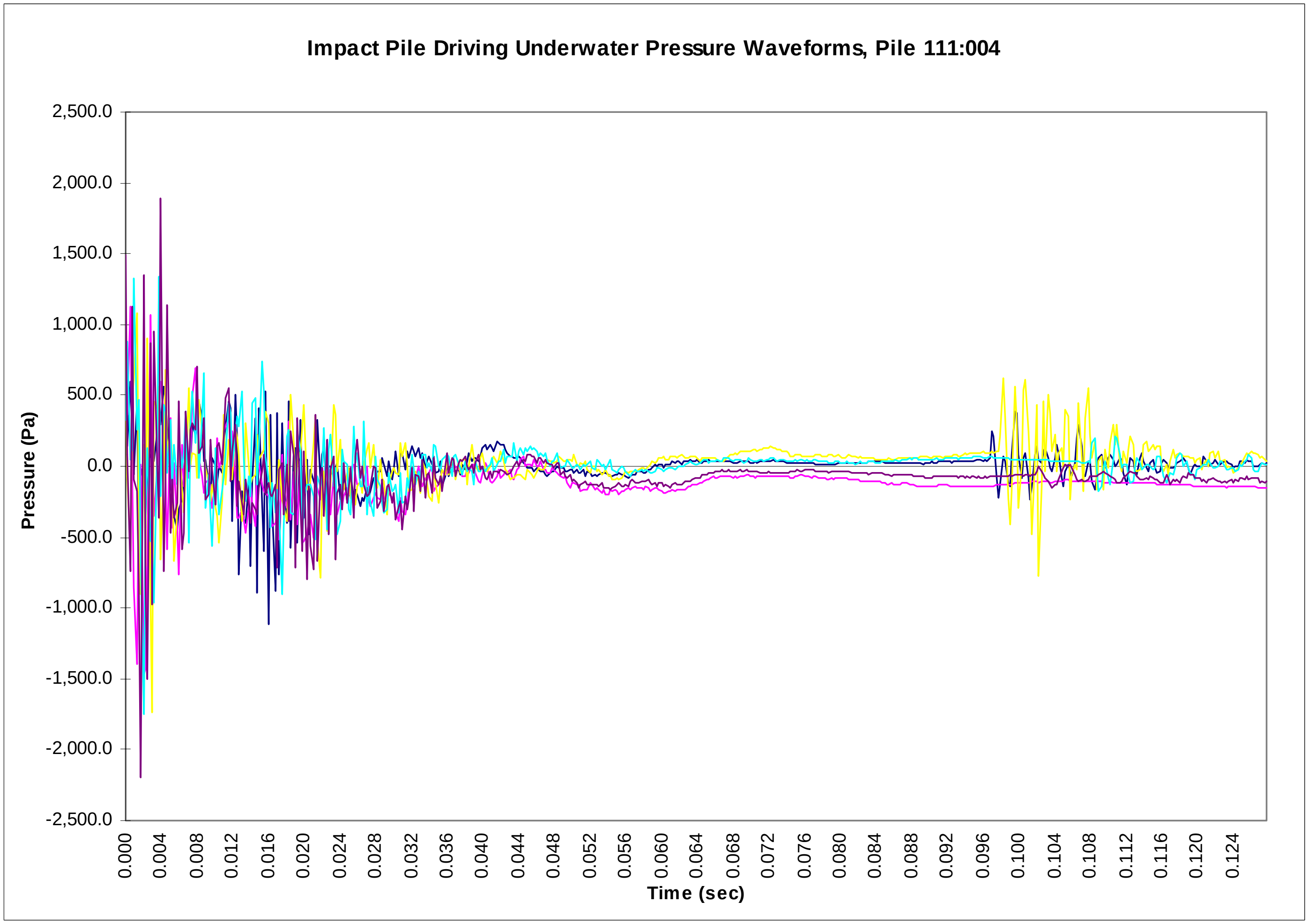

Figure 4.17. Time Domain Samples of Underwater Sound Signals from Several Pile Driver Strikes Recorded during Driving of Pile 111:004. This signal is characterized by a relatively long initial pulse of higher frequency sound followed by a lower energy low frequency waveform and a second short burst of higher frequency sound generated when the pile rebounded following initial impact and hit the pile driver head as it was being raised in preparation for the next strike.

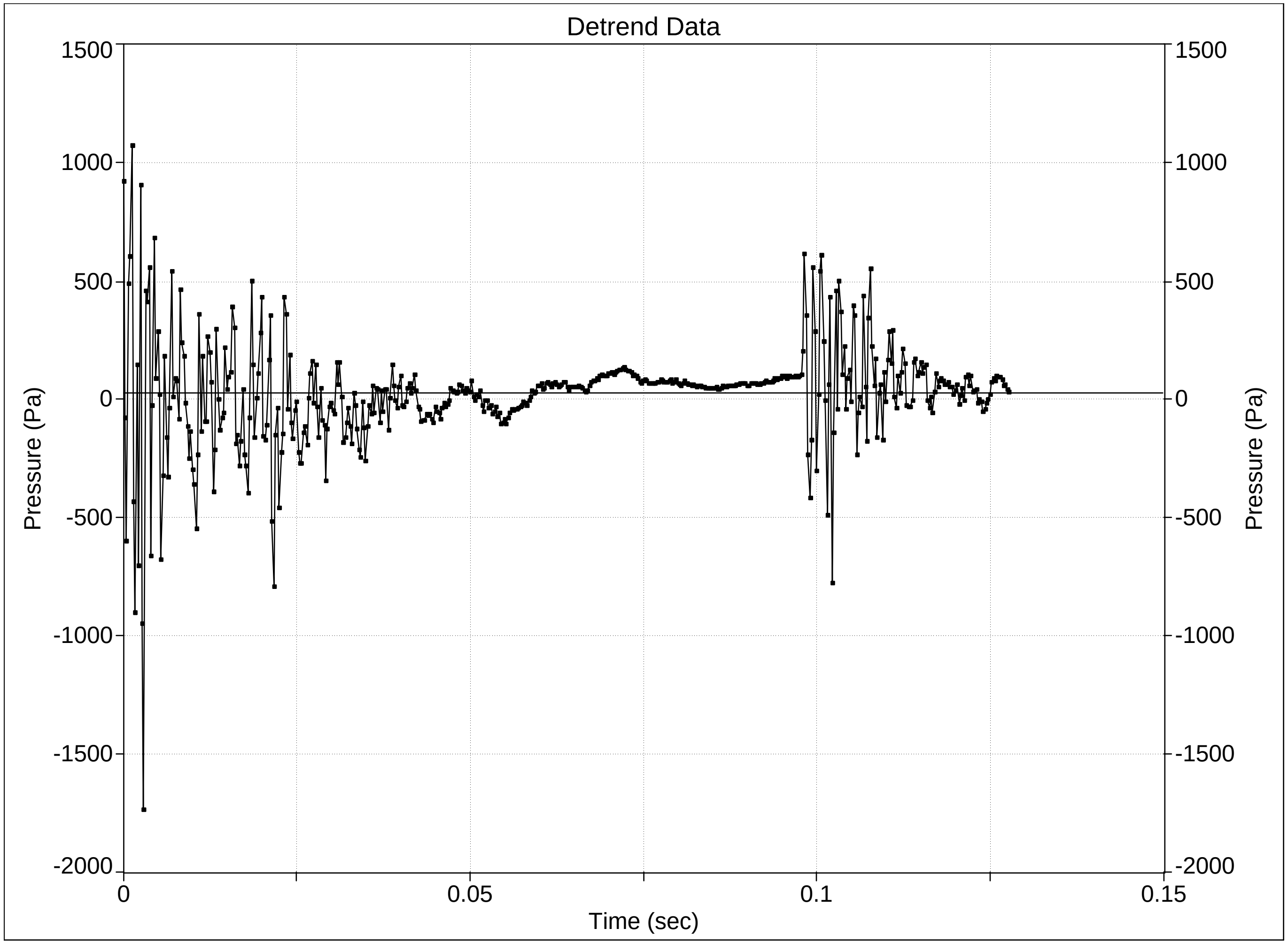

Figure 4.18. Underwater Sound Time Domain Signal Resulting from One of the Strikes Observed during Driving of Pile 111:004. This signal is one of those shown in Figure 4.17. This signal includes a combination of the features seen in the signals from the first two piles. These features include an initial high frequency burst due to initial impact then a low frequency waveform followed by a second higher frequency burst.

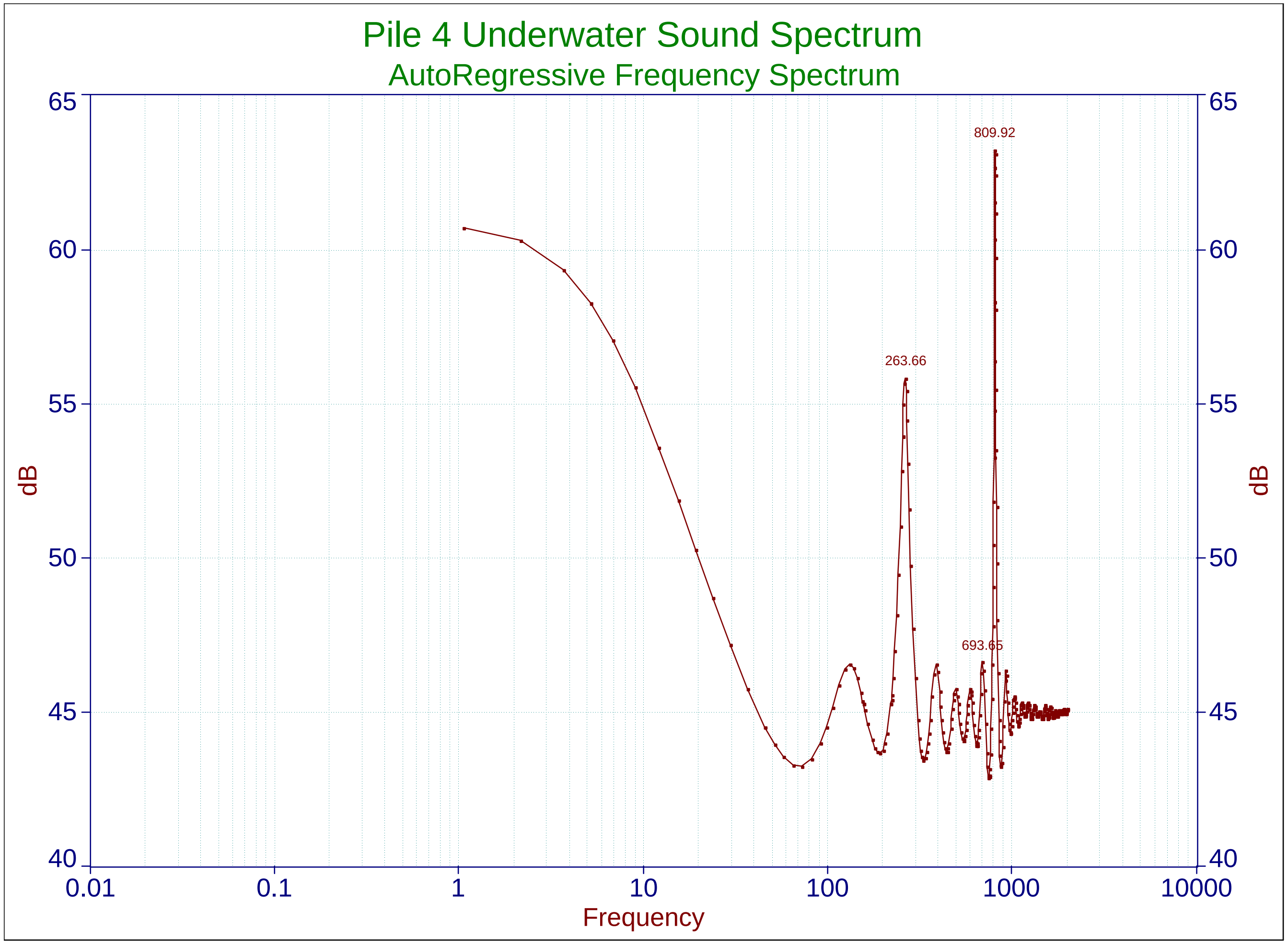

Figure 4.19. Frequency Spectrum Corresponding to Time Domain Sample of Underwater Sound Generated by the Pile Driver Strike Shown in Figure 4.18. The spectrum shows peaks at approximately 264 and 810 Hz, which are above the upper hearing threshold for salmonids. However, there is sound above background levels within the frequency range < 30 Hz known to elicit avoidance responses from juvenile salmonids. The levels of these frequency components are considerably above observed background levels.

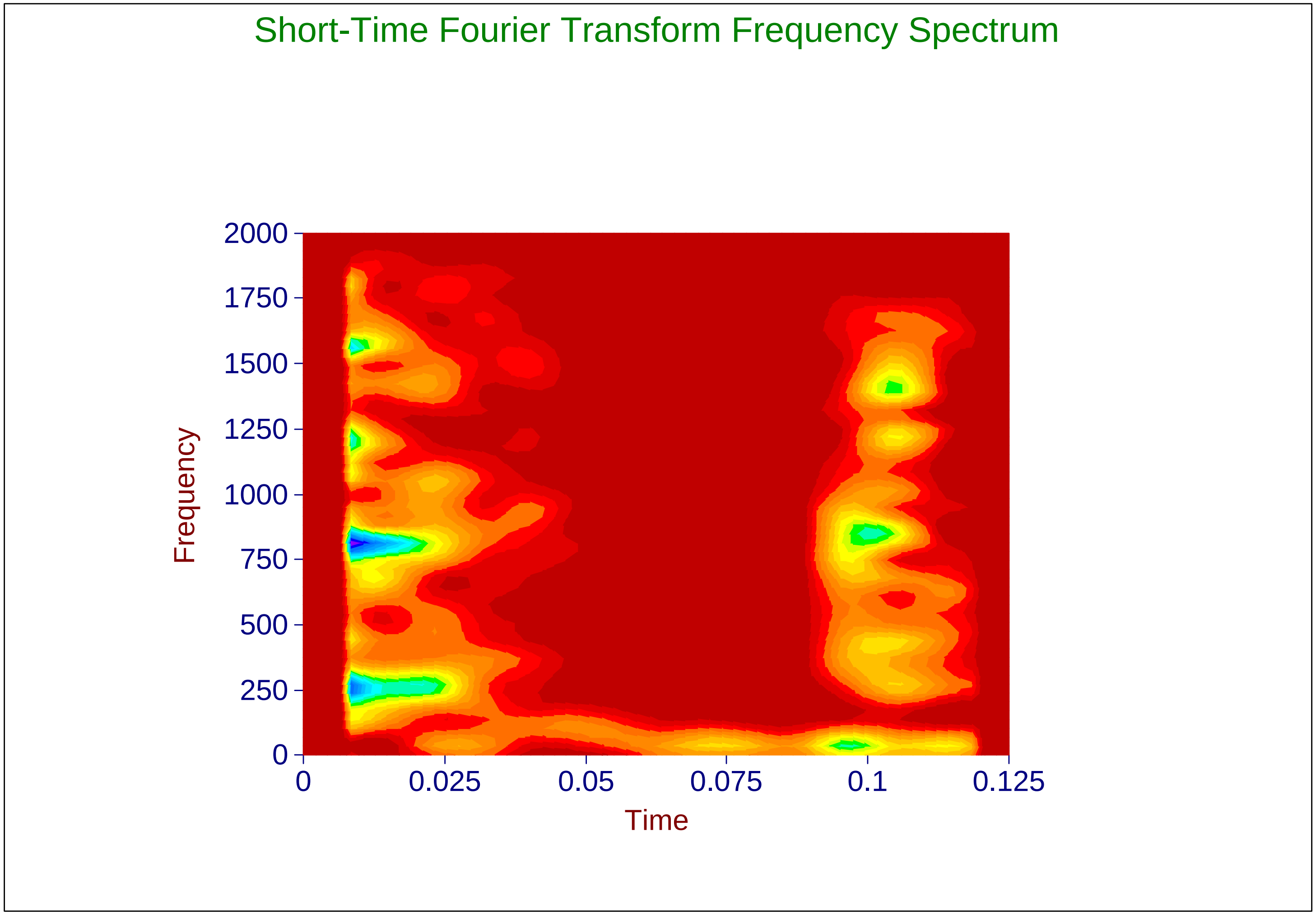

Figure 4.20. Time-Frequency Contour Plot Corresponding to the Pile Strike Shown in Figure 4.18. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude. This spectrum is characterized by a strong second occurrence of higher frequencies resulting from the pile rebounding and hitting the pile driver. In the case of this pile, sound generation persisted for 0.125 sec from the time of initial strike of the pile by the pile driver.

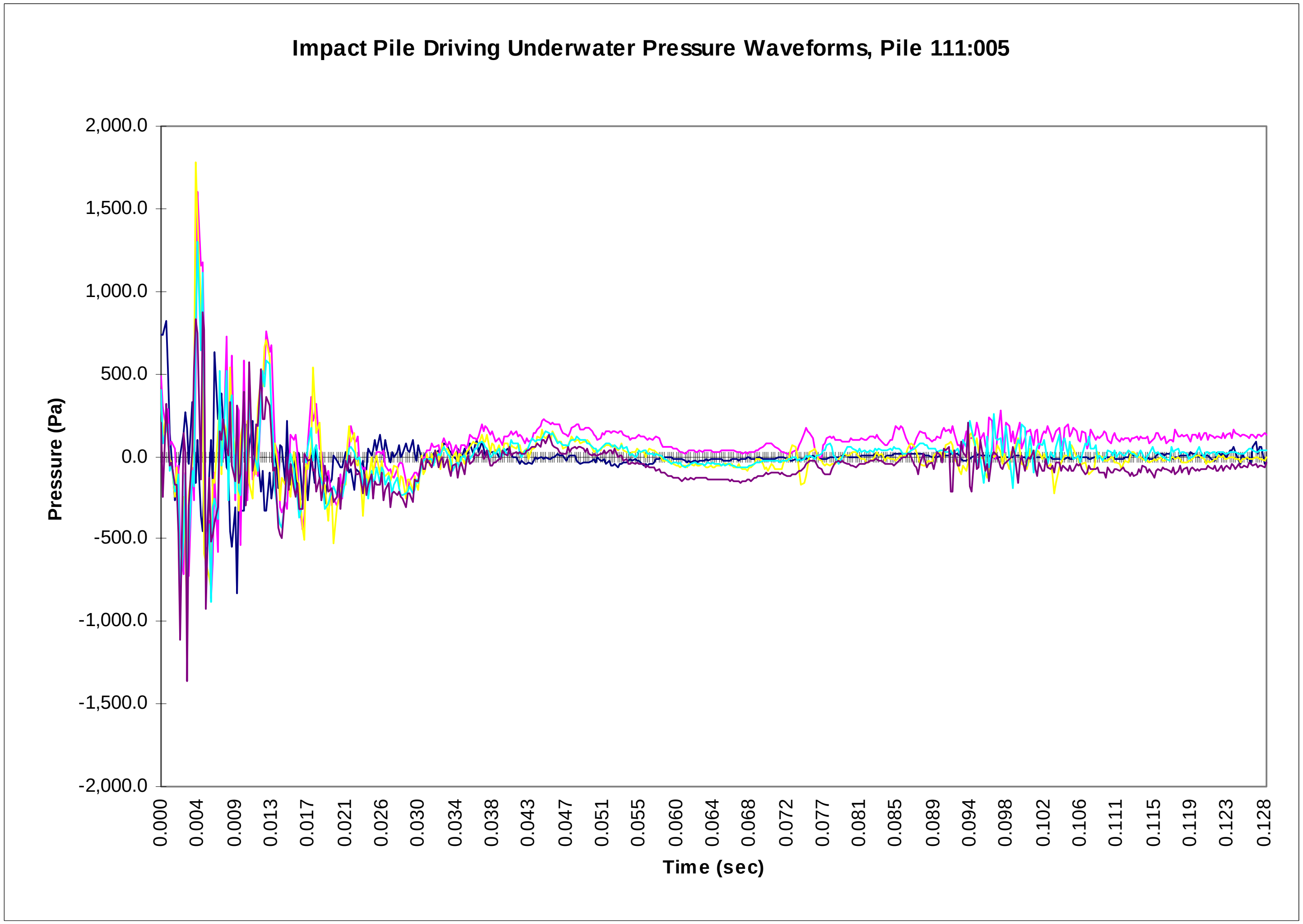

Figure 4.21. Time Domain Samples of Underwater Sound Signals from Several Pile Driver Strikes Recorded during Driving of Pile 111:004. This signal is characterized by an initial pulse of higher frequency sound followed by a lower energy low frequency waveform and a second, lower energy, short burst of higher frequency sound generated by a very light second strike when the pile rebounded following initial impact and hit the pile driver head as it was being raised in preparation for the next strike.

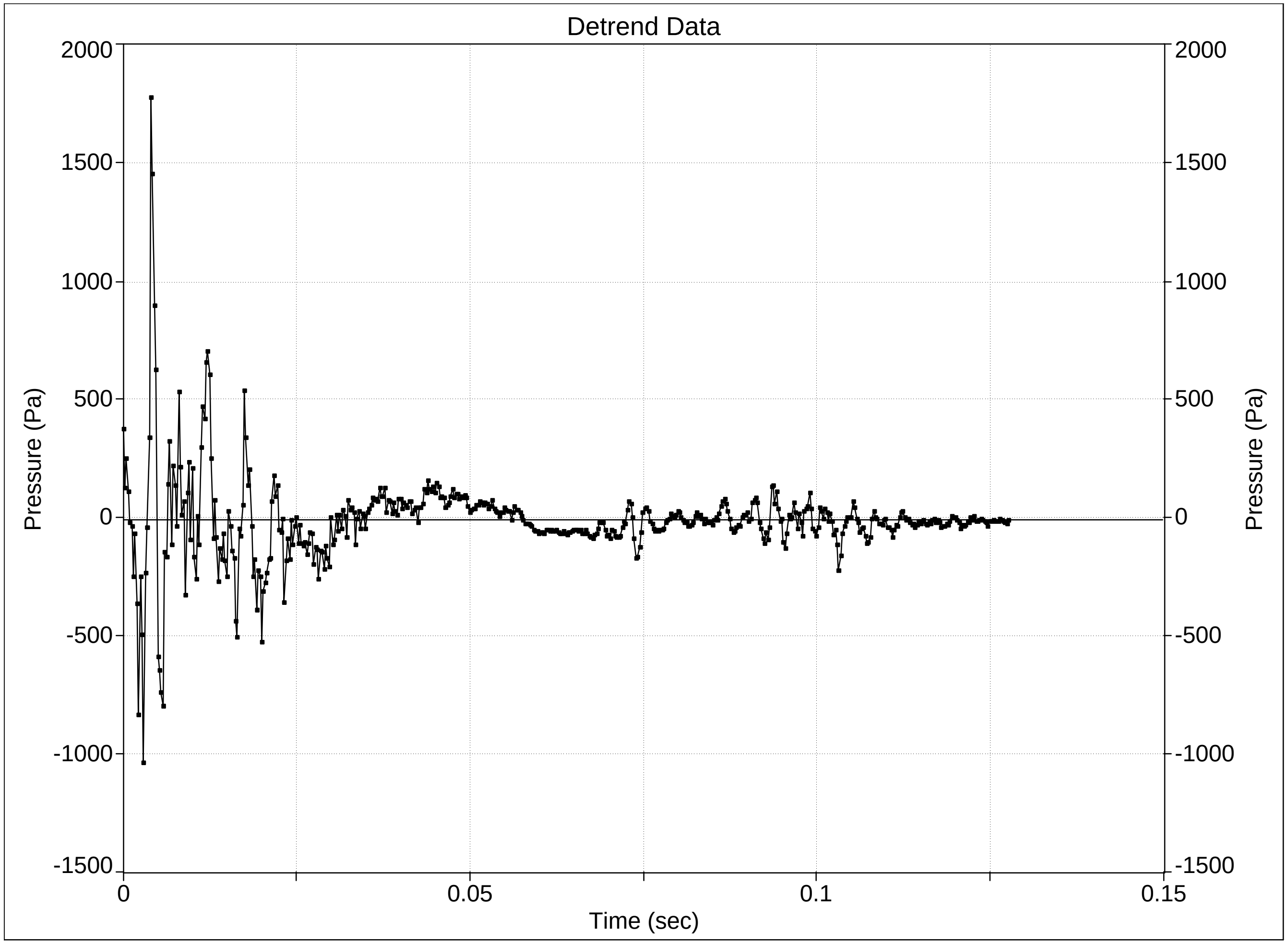

Figure 4.22. Underwater Sound Time Domain Signal Resulting from One of the Strikes Observed during Driving of Pile 111:005. This signal is one of those shown in Figure 4.21. This signal includes a combination of the features seen in the signals from the first two piles. These features include an initial high frequency burst due to initial impact then a low frequency waveform followed by a second higher frequency burst of very low energy resulting from a very light second impact.

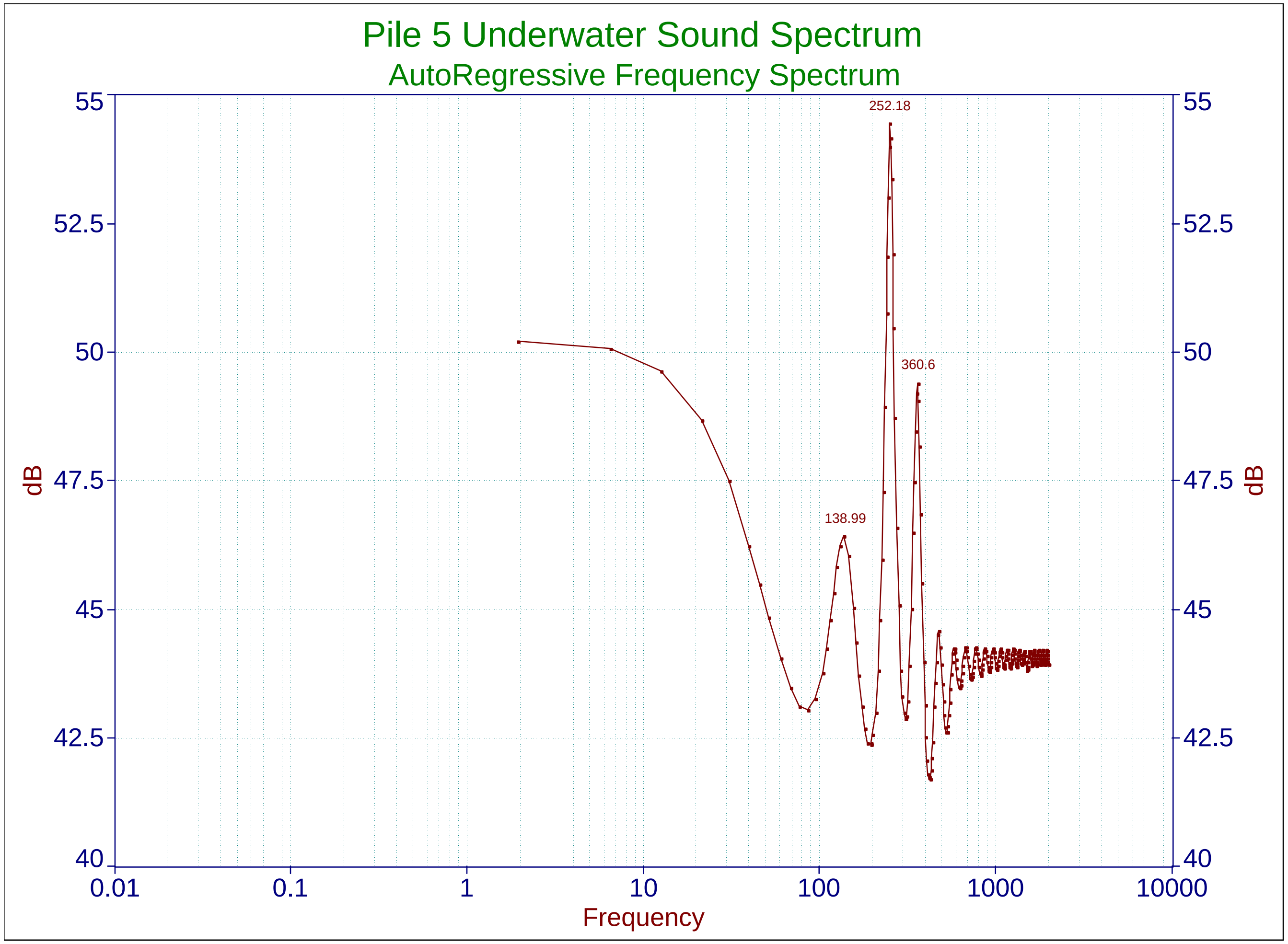

Figure 4.23. Frequency Spectrum Corresponding to Time Domain Sample of Underwater Sound Generated by the Pile Driver Strike shown in Figure 4.22. The spectrum shows peaks at approximately 139, 252, and 361 Hz, which, except for 139 Hz, are above the upper hearing threshold for salmonids. However, there is sound above background levels within the frequency range < 30 Hz.

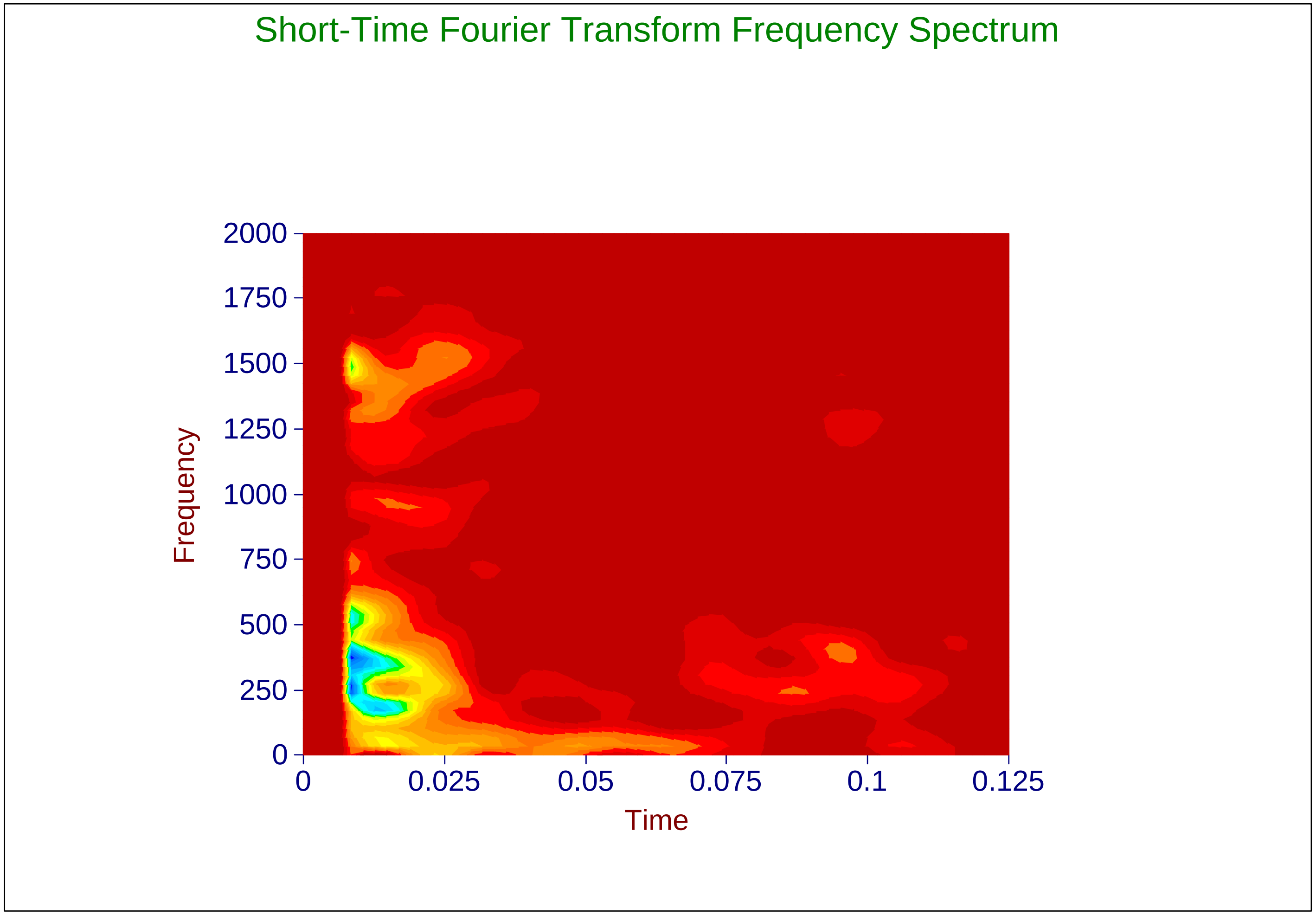

Figure 4.24. Time-Frequency Contour Plot Corresponding to the Pile Strike Shown in Figure 4.22. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude. While most of the higher frequency components are limited to the first 0.025 sec, there is a second occurrence of higher frequencies resulting from the pile rebounding and hitting the pile driver. Almost all of the sound generated by the strike is gone within 0.1 sec of the pile driver strike.

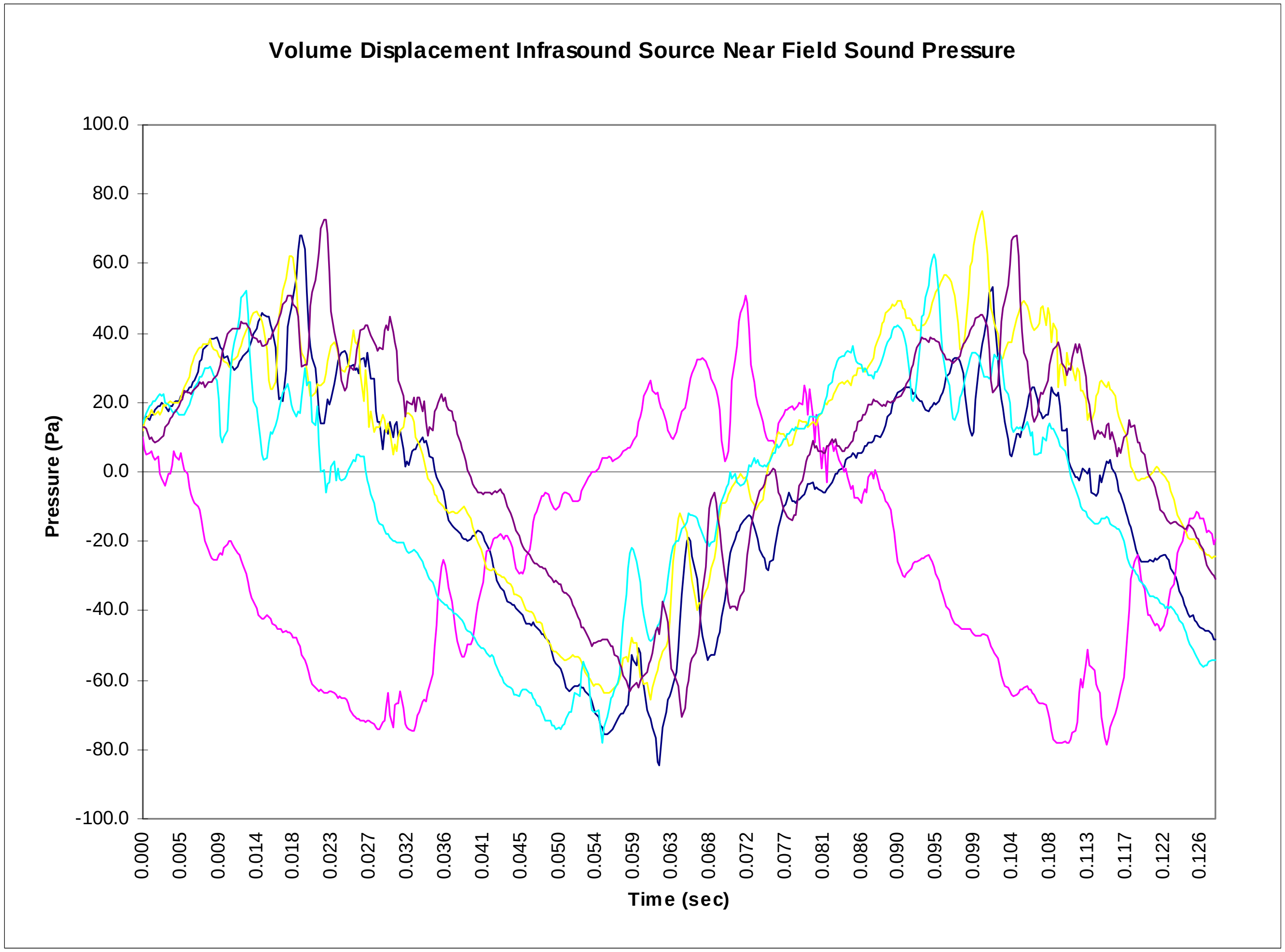

Figure 4.25. Time Domain Samples of Underwater Sound Signals from a Volume Displacement Infrasound Source Used in Experiments of the Avoidance Response of Juvenile and Adult Salmonids to Low-Frequency Sound. The signals are characterized by a very strong low frequency component modulated by a higher frequency caused by small-scale movements of the source piston.

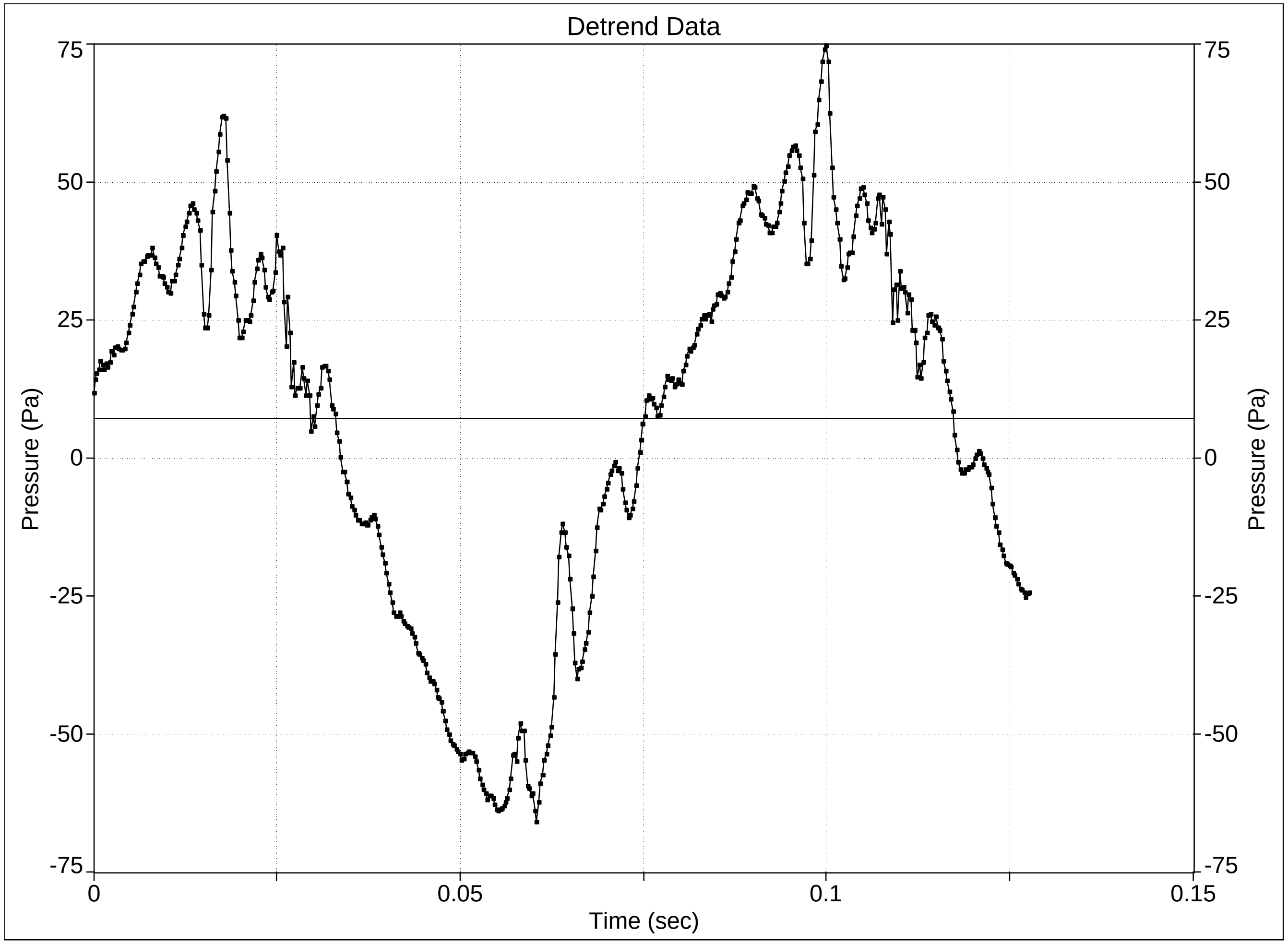

Figure 4.26. A Time Domain Sample of Underwater Sound Signal from a Volume Displacement Infrasound Source. This signal is one of those shown in Figure 4.25. This signal is characterized by a very strong low-frequency component modulated by a higher frequency.

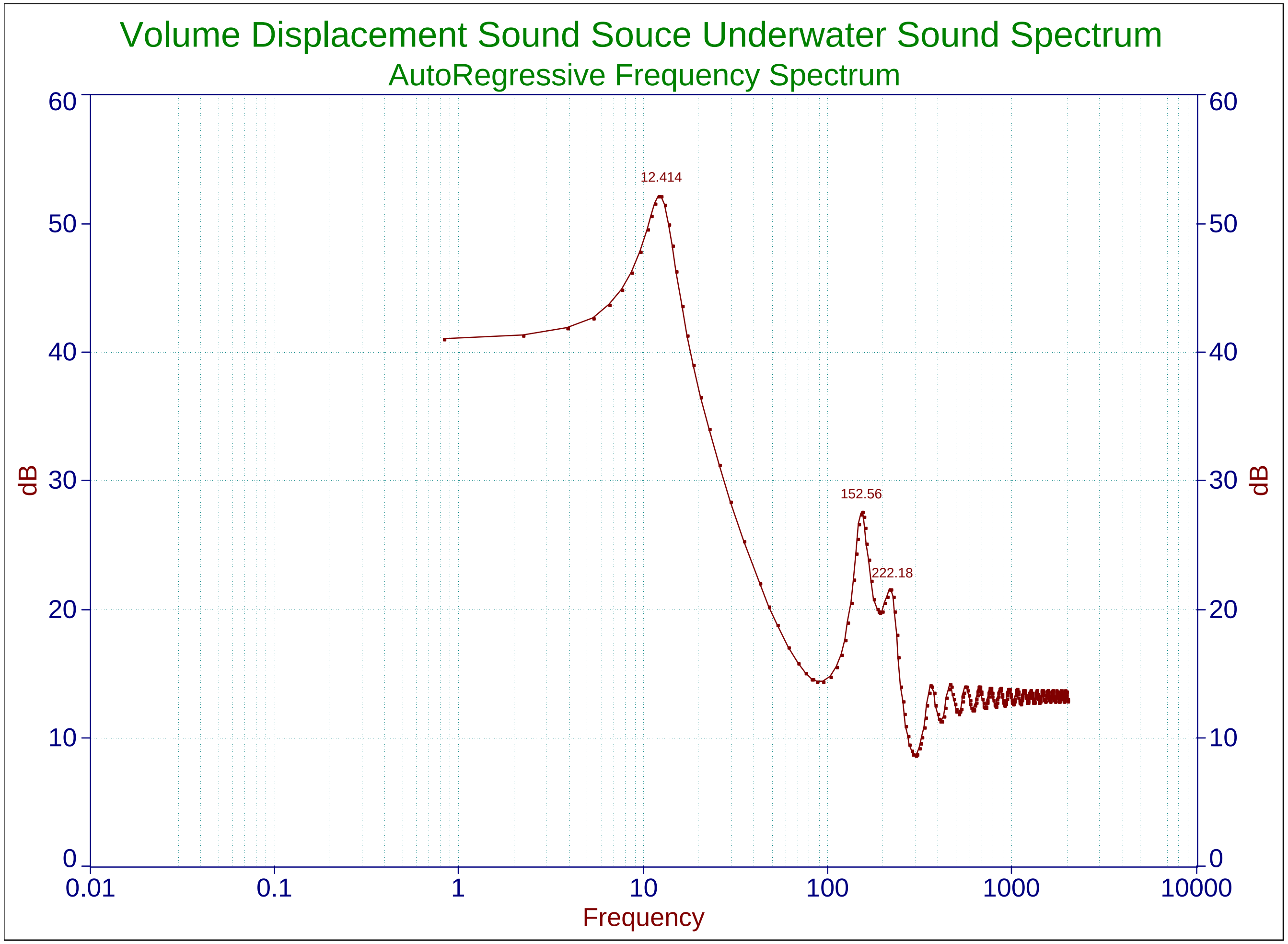

Figure 4.27. Frequency Spectrum Corresponding to Time Domain Sample of Underwater Sound Generated by a Volume Displacement Sound Source Used in Controlled Experiments of the Response of Salmonids to Infrasound. The dominant feature of this spectrum is the peak at 12.4 Hz followed by significantly lower peaks at 153 and 222 Hz.

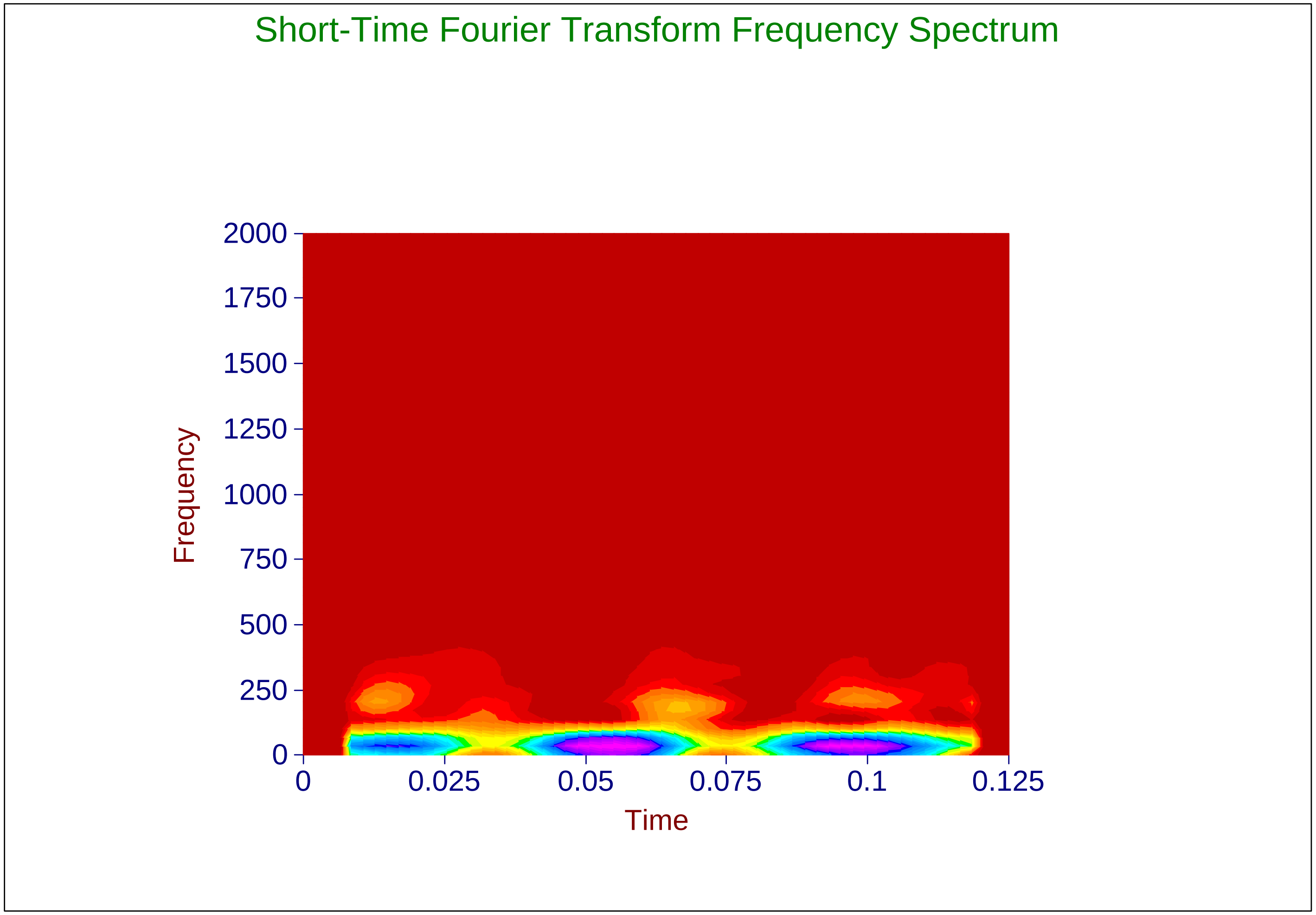

Figure 4.28. Time-Frequency Contour Plot Corresponding to the Volume Displacement Sound Source Signal Shown in Figure 4.27. This plot shows the time at which the various frequency components of the analyzed signal occurred and their relative magnitude.

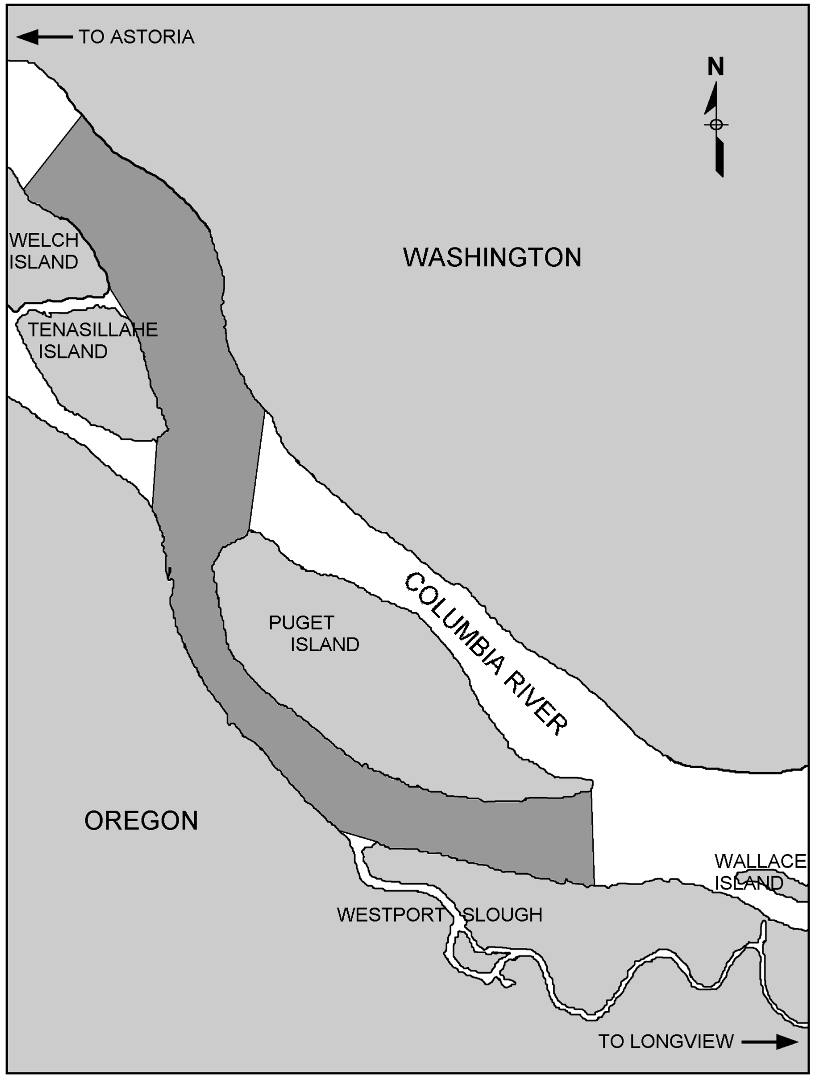

Figure 5.1. Section of the Columbia River Where Hydroacoustics Data (dark shaded area) Were Collected during Spring Sampling, May 19-22, 1997.

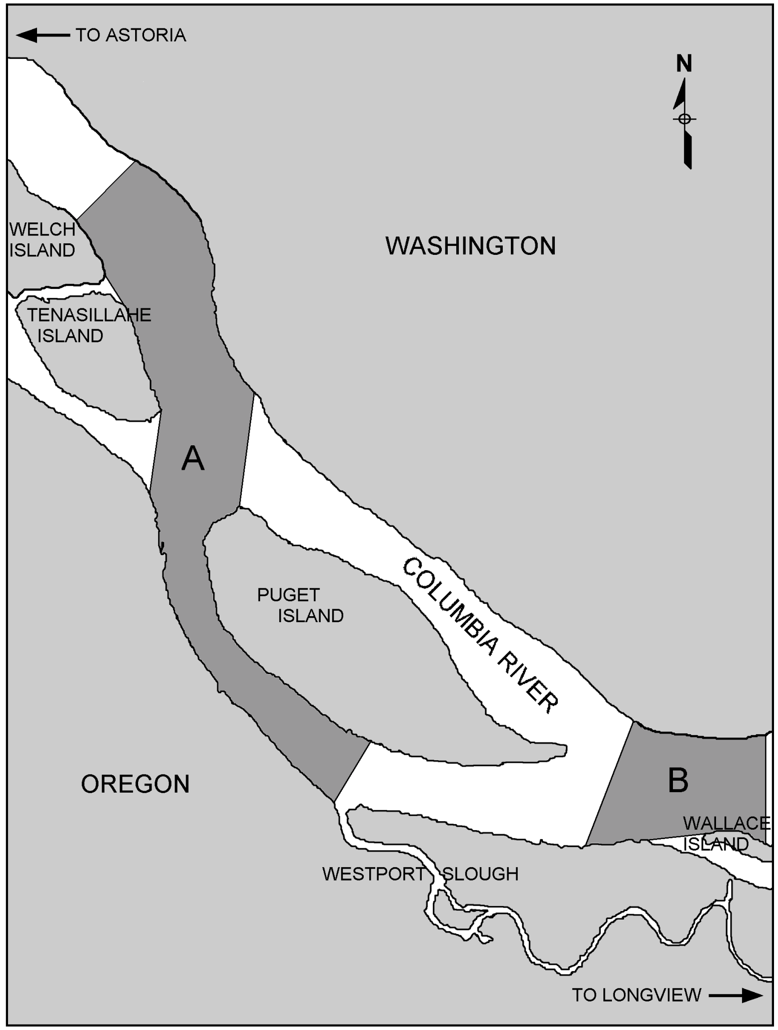

Figure 5.2. Section of the Columbia River Where Hydroacoustics Data (dark shaded area) Were Collected during Summer Sampling, July 22-24, 1997. A) downstream site and B) upstream site near the dredging operation.

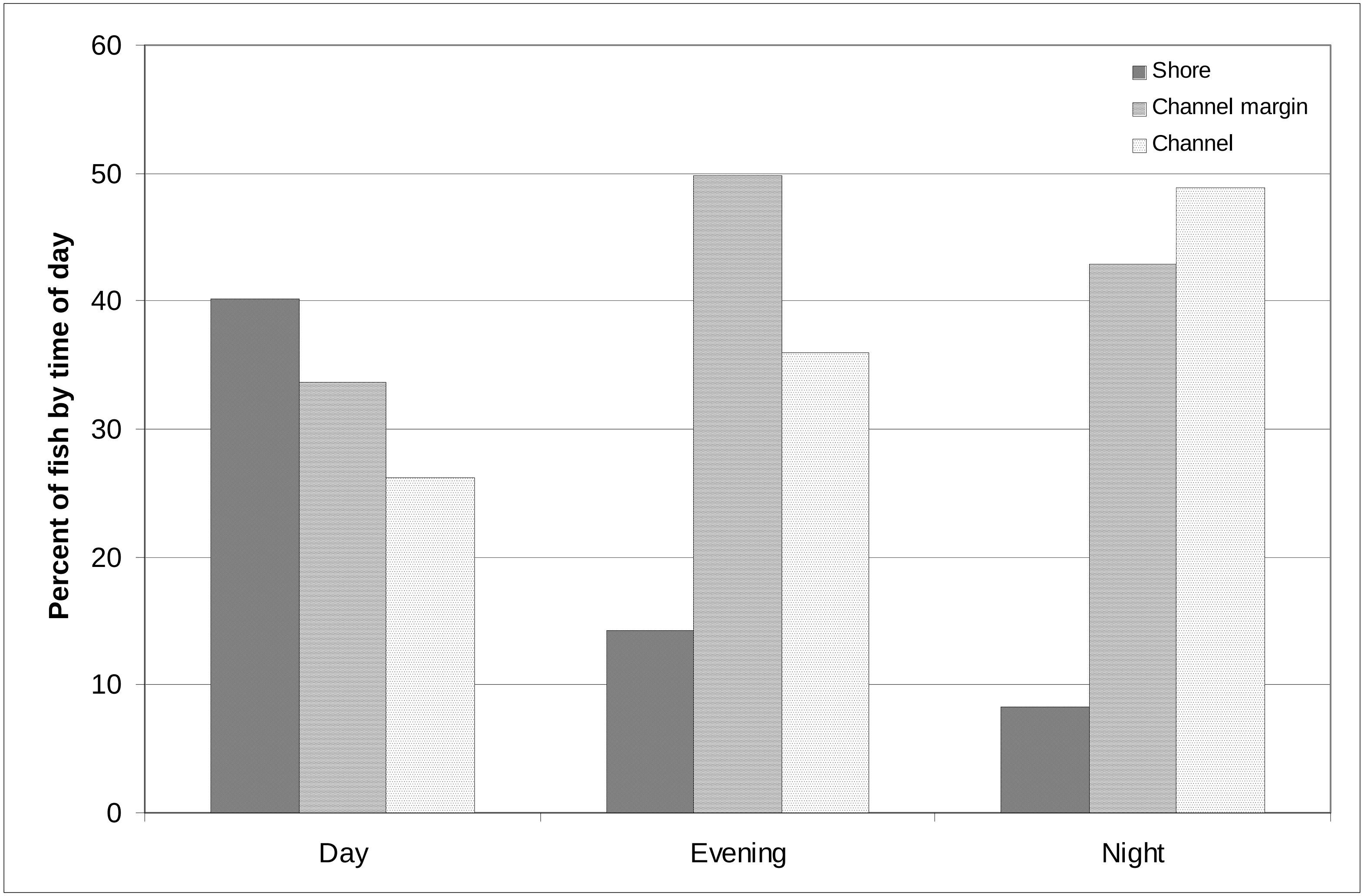

Figure 5.3. Percent of Fish Detected in the Channel, Channel Margin, and Inshore during the Day, Evening, and Night

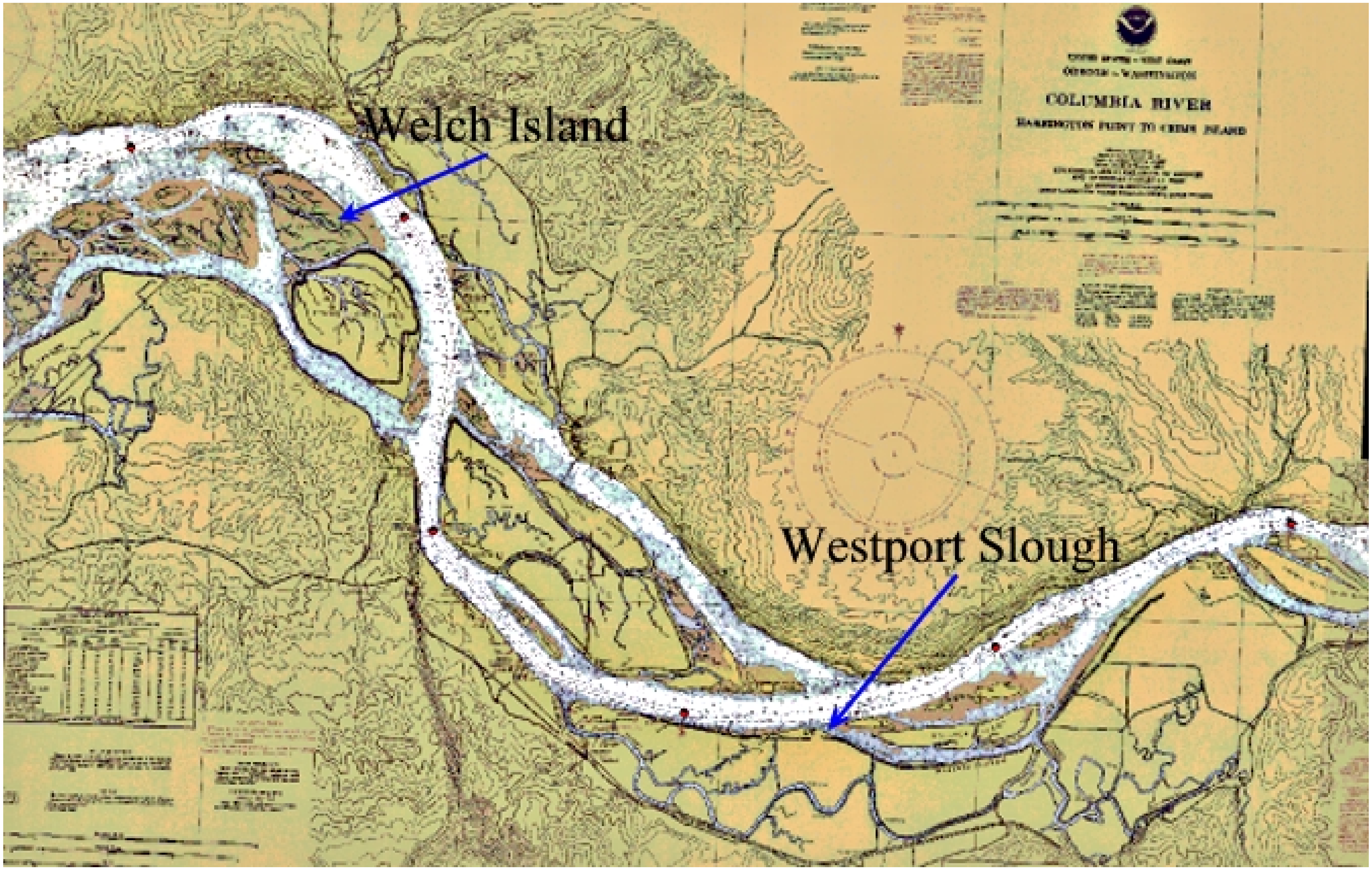

Figure 6.1. Map of the Jones Beach Reach on the Lower Columbia River Showing the Location of the Westport Slough and Welch Island, the Lower and Upper Bounds for Fish Distribution Hydroacoustic Surveys

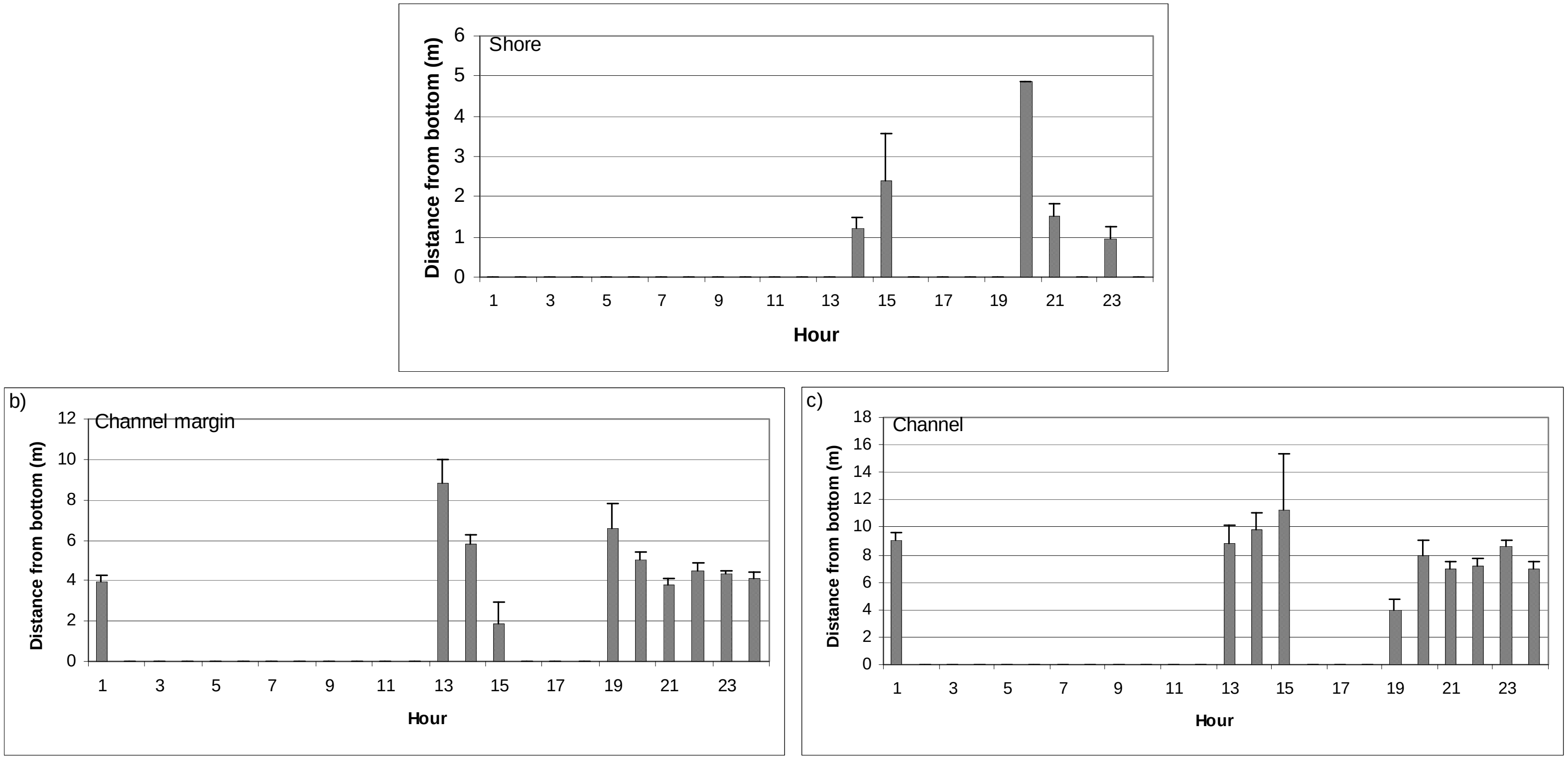

Figure 6.2. Mean Distance of Fish from the Bottom, by Hour, in Meters a) Inshore, b) Channel Margin, and c) Channel

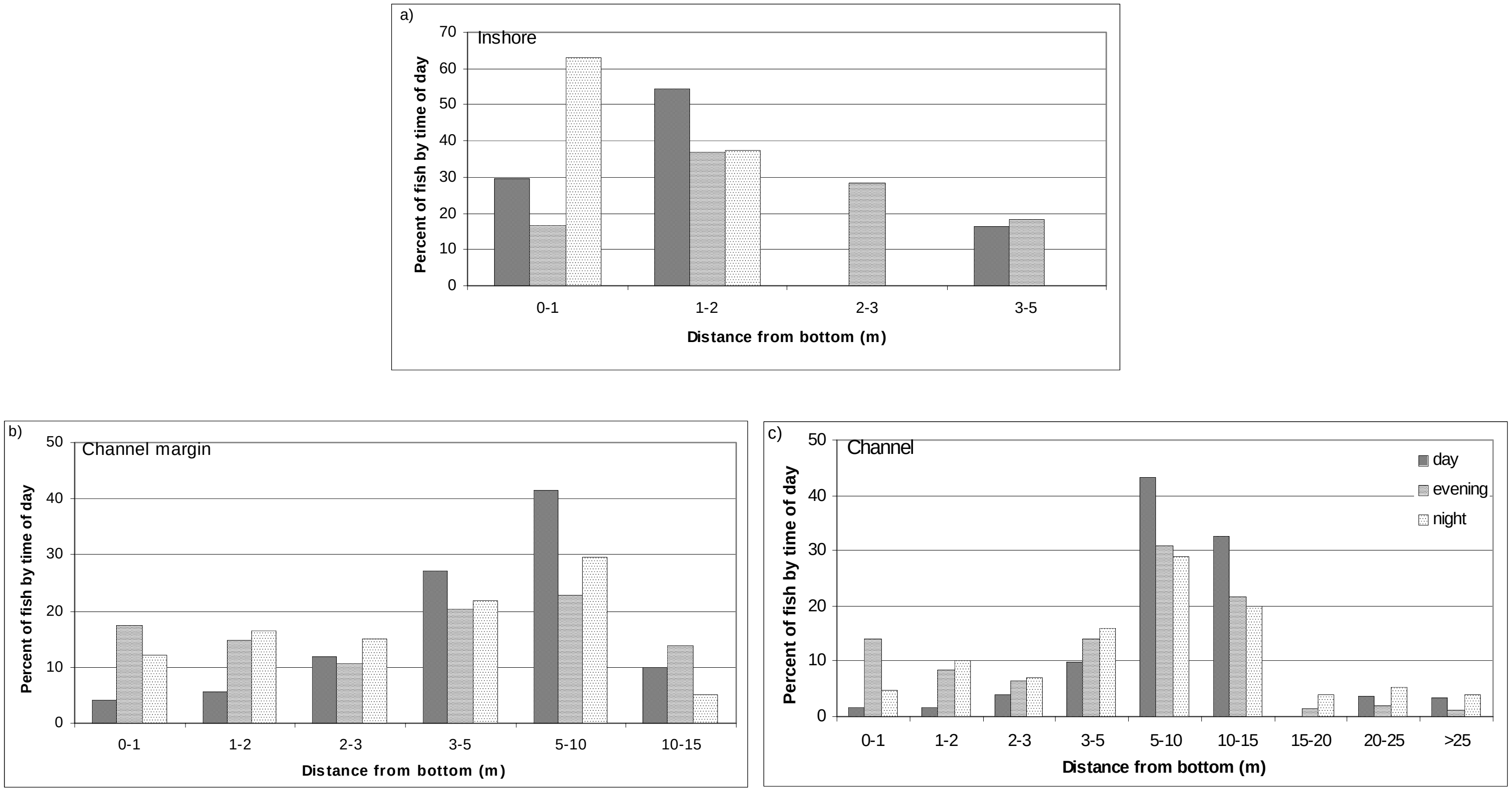

Figure 6.3. Vertical Distribution of Fish by Time of Day Divided into Depth Bins, with the River Bottom Being Zero Depth, for a) Inshore, b) Channel Margin, and c) Channel

Appendix A

Characterization of Underwater Infrasound Generated by Vibratory Pile Driving within the Context of the Characteristics of Sound Known to Result in Avoidance Response by Juvenile Salmonids

Appendix A

Characterization of Underwater Infrasound Generated by Vibratory Pile Driving within the Context of the Characteristics of Sound Known to Result in Avoidance Response by Juvenile Salmonids[(a)]

Marine construction, including pile driving, is regulated to reduce potential impacts to migrating salmon and steelhead. The reason frequently given for limiting the time and place where pile driving can be conducted is that the generation of underwater sound may affect the behavior of migrating fish. However, until recently there was very little data to document the nature of sound generated by pile driving or the response of fish, particularly salmon and steelhead, to sound.

The construction of a new pier by Oregon State University (OSU) at the Hatfield Marine Sciences Center in Oregon offered the opportunity to measure the sound field generated by vibratory pile driving. Vibratory pile driving is one of the two most commonly used methods to drive piles in the Pacific Northwest, the other being impact pile driving. A vibratory pile driver consists of a heavy weight and a pneumatically driven mechanism that vibrates the pile in the plane perpendicular to the long axis of the pile. The combination of the weight on the pile and the vibratory motion forces the pile into the substrate. The maximum range of the vibratory hammer's oscillatory motion is approximately 2 inches where the vibrator attaches to the top of the pile. The sound field generated by vibratory pile driving is a result of the oscillatory movement of the pile in the water as it is being driven.

A.1 Study Methods

Sound field measurements were made at the new pier on August 29 and 30, 1996. On August 29, sound measurements were made from two different locations along the pier as fender piles were being driven along the perimeter of the pier. The fender piles being placed at this site were steel pipe approximately 9 inches in diameter and 60 feet long. Logistics and safety considerations prevented underwater sound measurements from being made at ranges less than 75 feet on August 29.

On August 30, a boat and operator were made available by OSU, which permitted underwater sound measurements to be made in the immediate vicinity of the piles being driven. The location of the hydrophone used to acquire the sound signals relative to the location of the piles was optimal for a series of six piles being driven along the outer perimeter of the pier. The range from the hydrophone to the piles was less than 50 feet for all six piles.

The equipment used to acquire and process the sound signals is given in Table A.1 below. The hydrophone, charge amplifier, and DAT recorder were used to acquire and store raw sound signals. The signal processing hardware and software was used to process and analyze the acquired signals.

(a) This report was prepared for Oregon State University in December 1996 by Thomas J. Carlson while with the U.S. Army Corps of Engineers – Portland District.

Table A.1. Equipment Used to Process Time Signals

Instrument	Manufacturer	Model No.
Hydrophone	Bruel & Kjaer	8104
Charge Amplifier	Bruel & Kjaer	2635
Digital Audio Tape Recorder	Sony	PC204Ax
Signal Processing Digital Acquisition Board and Software	National Instruments	DSP-2200, Joint Time- Frequency Analysis Toolkit

The frequency response of the B&K 8104 hydrophone is flat from DC to 10 kHz. Over this range its receiving sensitivity is 53.7 μV/Pa. The B&K 2635 charge amplifier is designed so that the calibration constant for the hydrophone can be input to the amplifier thereby permitting the amplifier output to be read directly in terms of sound pressure level in Pa. The charge amplifier also permitted control of the gain of the output signal so that the dynamic range of the DAT recorder could be optimized. The frequency range of the Sony instrumentation digital audio tape recorder is DC to 20 kHz. The frequency response of the recorder over this range is essentially flat.

The hydrophone cable was attached to a line marked in foot increments so that the hydrophone could be easily deployed at any depth to 30 feet, the length of the hydrophone cable, while keeping the hydrophone cable free of any load. This cable length was sufficient since the maximum depth of water near the pier during the time measurements were made was 29 feet. The hydrophone was held in position by a weight attached to the bottom of the line supporting the hydrophone cable and a buoy attached to the line at the surface. The hydrophone was mechanically decoupled from the boat. The buoy was attached to the line by a snap so that its position could be changed to permit positioning of the hydrophone at different depths.

Table A.2 below shows the identification number of the pile being driven, the range from the hydrophone buoy to the pile, the depth of the hydrophone, the start and stop times for each pile, and the time required to drive each pile.

With the exception of the first two piles, all of the underwater sound measurements were made at different depths. This sampling strategy was selected to obtain sound measurements near the surface and bottom boundaries in addition to midwater. Although the distance between the piles and the hydrophone was short, it was unclear what effect, if any, the surface and bottom might have on the sound field. While the sampling method implemented does not permit evaluation of the effects of the boundaries, it did permit observation of the sound field generated by vibratory pile driving over the vertical range available to fish. While the use of a single hydrophone to sample a complex three-dimensional sound field is limiting, the observations obtained are felt to be representative of the sound field generated by vibratory pile driving.

Table A.2. Hydrophone Depth and Distance to Each Pile and Pile Driving Time

Pile Id Number	Pile To Hydrophone Distance in Feet	Hydrophone Depth in Feet	Pile Driving Start Time in HHMMSS	Pile Driving End Time in HHMMSS	Time Required to Drive Pile in HHMMSS
ID01	50	25	110008	110033	000026
ID02	48	25	110152	110229	000037
ID03	46	20	110401	110451	000050
ID04	46	5	111007	111027	000020
ID05	46	10	110803	110902	000059
ID06	48	15	110619	110710	000051
HHMMSS = hours, minutes, seconds					

The recorded sound measurements were processed using a National Instruments Joint Time-Frequency Analysis (JTFA) software toolkit and DSP-2200 digital data acquisition board. The signals were digitized by taking 1,024 measurements at a sampling rate of 1 kHz. The toolkit and digital acquisition board filtered the data prior to digitization to remove frequencies higher than the Nyquist frequency at the 1-kHz sampling rate. Initial analysis of background samples showed significant energy at frequencies below 2 Hz resulting from hydrostatic (not sound) pressure variation due to low-amplitude wave action. The analysis also showed that background energy levels were down over 30 dB at 2 Hz with no significant energy above 2 Hz within the frequency range analyzed. The energy at these low frequencies was removed using features available for that purpose in the JTFA toolkit as an initial step in power spectrum analysis of the sound generated by pile driving.

The output of the JTFA toolkit included a one-sided power spectrum and time domain waveform in a spreadsheet format. The sound signal tape recording for each of the piles was sampled five times at locations approximately equally spaced throughout the time required to drive each pile. Five one-sided power spectra and time domain waveforms were obtained for each pile. All of the power spectra and waveforms were placed in a Microsoft Excel workbook which was organized by pile. Using Excel functions, the spectra and waveforms were adjusted to compensate for DAT recorder gain and differences in charge amplifier settings between piles and to compute the mean, standard deviation, and 90% confidence interval for each set of power spectra. The individual one-sided spectra were multiplied by two to obtain the total power spectra prior to statistical analysis.

A.2 Results

The results of the six-pile measurement series are summarized in Figures A.1 through A.18. There are three figures for each pile. The first figure for each pile is a plot of the average power spectrum for the set of five measurements made for each pile. The second figure is a plot of the individual power spectrums for each of the five measurements for each pile. The last figure is a plot of a representative time domain waveform for each pile.

The average power spectrums for each pile are very similar. Each spectrum shows spikes at low frequencies that correlate with features distinguishable in the time domain waveforms. The correlation between the time domain waveforms and the power spectra are particularly clear for piles 1, 2, 3, and 6. For all piles, most of the energy in the sound field is located at frequencies below 50 Hz with approximately half at infrasound frequencies. While the location of spectral maxima remains quite consistent from one sample to another for any pile, there is significant variation in the total power at any particular frequency from sample to sample for each pile.

The data presented also includes a set of two figures obtained from a study that characterized the sound field generated by a volume displacement infrasound source (Carlson 1996). Figures A.19 and A.20 show the sound spectrum and time domain waveform for measurements of the sound field generated by the volume displacement infrasound source. These figures show that the volume displacement infrasound source generates sound with energy concentrated in a relatively narrow band around 11 Hz, which is within the range of maximum sound energy produced by vibratory pile driving. A comparison of the time domain waveform of the infrasound source with that of vibratory pile driving also shows similarities. Both sources show easily detectable low-frequency features with the major difference being the relative "cleanliness" of the volume displacement source, a result of its design to generate sound within a relatively narrow band.

A.3 Discussion

After several decades of research, it has been learned that salmonids respond to the flow component within the near field of volume displacement infrasound sources (Carlson 1994; Knudsen, Enger, and Sand 1992, 1994). Recently completed studies have shown that wild and hatchery Pacific salmon and steelhead from swim-up fry to smolt exhibit an innate avoidance response to infrasound within the frequency range of 8 to 12 Hz at water particle acceleration greater than 0.01 ms^{-2}. (Knudsen, Schreck, and Knopp 1996; Mueller et al. 1998). There is no ambiguity, salmonids respond to infrasound. In addition, the characteristics of sound to which they exhibit a definite avoidance response are specific and are located within the near field of the sound source, not the propagating portion of a sound field. While there is still some uncertainty about the frequency range below 100 Hz within which salmonids will respond, it is well established that salmonids respond primarily to water particle motion and not pressure.

The fact that salmonids respond primarily to water particle motion and not pressure presents sound field assessment challenges since the relationship between sound pressure and particle motion is complex within the near field of sound sources. The complication arises because it is considerably easier and cheaper to measure sound pressure than water particle motion. Given this complication and a limitation to measure sound pressure only, the data acquisition and analysis strategy selected for this study has two parts. The first part is the use of sound pressure measurements to characterize the spectral composition and the time domain waveform (variation in sound pressure with time) of the sound field generated by vibratory pile driving. The second part is to compare the characteristics of the sound field generated by vibratory pile driving with similar measures of the sound field generated by a volume displacement infrasound source. The volume displacement infrasound source measurements provide the characteristics of infrasound known to cause an avoidance response by juvenile salmonids. These characteristics are used as a template for interpretation of the vibratory pile driving sound data within the context of probable impact on juvenile salmonid behavior.

The first step in evaluation of the sound field generated by vibratory pile driving is to compare the frequency content of the vibratory pile driving average power spectra for individual piles with the power spectra for the volume displacement infrasound source. Comparison of the spectra show that vibratory pile driving generates a sound field with considerable energy in the infrasound frequency range at frequencies where salmonid avoidance behavior has been observed.

In general, the power levels are similar for the volume displacement infrasound source and vibratory pile driving, particularly if the power in the individual vibratory pile driving average power spectra are integrated over frequencies in the infrasound region ($\leq$20 Hz). The range between the hydrophone and the source for the volume displacement source was approximately 8 feet while that for the piles was approximately 50 feet. Under free field conditions for a propagating sound wave, this difference in range would imply that, given equivalent source strengths, sound pressure levels should be approximately six times lower at 50 feet than 8 feet while particle motion would be approximately 125 times lower. The difference is the rates of decay of sound pressure and particle motion which are known to be $Range^{-1}$ and $Range^{-3}$ respectively (Kalmijn 1988). Even considering the fact that the sound pressure measurements for both vibratory pile driving and the volume displacement infrasound source were made in the near field (at infrasound frequencies), it seems reasonable to conclude that, in general, the source level of the piles was higher than that for the volume displacement source. The implication here is that vibratory pile driving generates infrasound at sufficiently high levels to affect the behavior of juvenile salmonids. Quantification of exactly how much higher the source level was for the piles than for the volume displacement source would require considerably more data that that available in the present data set.

The final questions are "what is the probable response of salmonids to vibratory pile driving?" and "at what range from the piles is avoidance response likely?" Controlled experiments with volume displacement infrasound sources determined the threshold for near field particle acceleration above which salmonids exhibit avoidance response is 0.01 ms^{-2}. The range to this acceleration value for the volume displacement source characterized in terms of power spectrum and time domain waveform in Figures A.19 and A.20 has been determined to be approximately 10 feet (Carlson 1996). If the source level of the piles (i.e., the source level of an incremental portion of the pile, discounting integration over the pile or any consideration of directivity) in terms of water particle acceleration was similar to that of the volume displacement infrasound source, the region within which fish would show avoidance would look something like a cylinder with a radius of 10 feet centered on a pile. If the source strength of the pile was 10 times that of the volume displacement infrasound source, in terms of maximum water particle acceleration at the face of the pile, the radius of the region above the avoidance threshold would only slightly more than double to approximately 22 feet because of the rapid decay in particle motion with distance, assuming free field conditions.

It appears unlikely that the vibratory pile driving would cause avoidance response by juvenile salmonids beyond the immediate vicinity (~20 to 30 ft) of the pile driving activity, given the conditions observed at the OSU pier. This conclusion is supported by the similarity between vibratory pile driving and volume displacement infrasound source observations in power levels at infrasound frequencies, the physical parameters for decay of the local flow portion of the near field of a sound source, the results of replicated controlled experiments documenting the response of juvenile salmonids to infrasound, and the threshold for observed avoidance responses.

An additional element worth discussing is the duration of the generation of infrasound during vibratory pile driving. The average time it took to drive a pile was 40.5 seconds and the total time the vibratory hammer was operating to drive all six piles was 4 minutes 3 seconds. A typical day of pile driving consists of many activities such as placement of jigs, preparation of piles, and many other related tasks that must be completed before pile placement can begin. Once all the preparations for a series of piles has been completed the actual time required to drive the piles can be very short, as this series demonstrates. This data makes it clear that vibratory pile driving construction activities do not result in continuous generation of infrasound. In fact, the amount of time infrasound is generated is most likely, for most projects, a very small portion of a work day.

The relatively short time during which infrasound is generated by vibratory pile driving, in association with the likely relatively short range of the component of the total sound field to which salmonids show avoidance response, leads to the conclusion that this type of construction activity is unlikely to have a significant impact on migrating salmonid behavior.

A.4 References

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Carlson, T.J. 1994. *Use of Sound for Fish Protection at Power Production Facilities: A Historical Perspective of the State of the Art*. Project 92-071, Pacific Northwest National Laboratory, U.S. Dept. of Energy, Bonneville Power Administration.

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Knudsen, F.R., P.S. Enger, and O. Sand. 1992. "Awareness Reactions and Avoidance Responses to Sound in Juvenile Atlantic Salmon, *Salmo salar L." Journal of Fish Biology* 40:523-534.

Knudsen, F.R., P.S. Enger, and O. Sand. 1994. "Avoidance Responses to Low Frequency Sound in Downstream Migrating Atlantic Salmon, *Salmo salar L.*" *Journal of Fish Biology* 40:523-534.

Knudsen, F.R., C. Schreck, and S. Knapp. 1996. *Avoidance Responses and Habituation to Low Frequency Sound in Juvenile Steelhead and Chinook.* (submitted for publication).

Mueller, R.P., D.A. Neitzel, W.V. Mavros, and T.J. Carlson. 1998. *Evaluation of Low and High Frequency Sound for Enhancing Fish Screening Facilities to Protect Outmigrating Salmonids.* Report to the Bonneville Power Administration by the Pacific Northwest National Laboratory, Richland, Washington.

Figure 1: Average Underwater Sound Power Spectrum, Vibratory Pile Driving, Pile No. 1

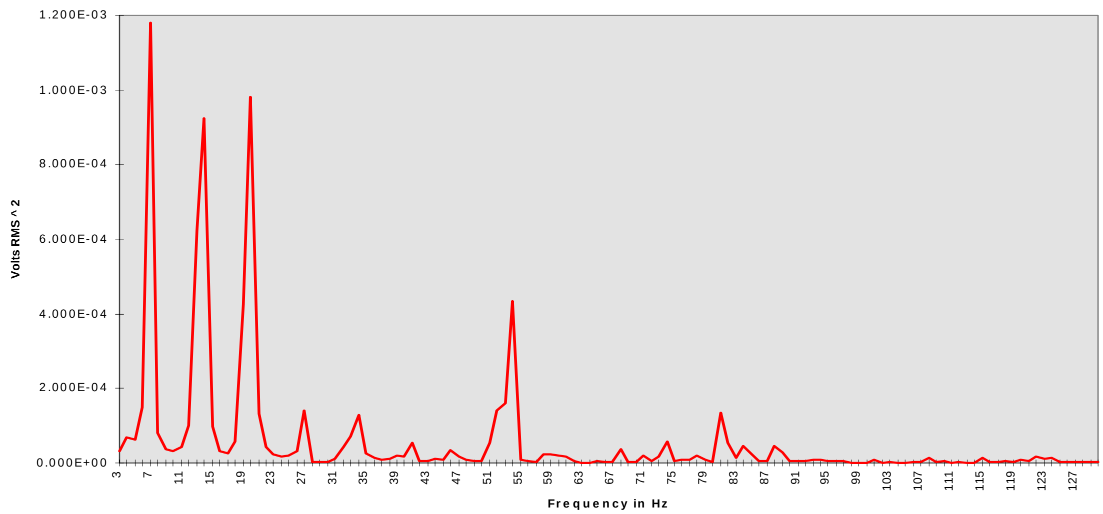


Figure 2: Individual Underwater Sound Power Spectra, Vibratory Pile Driving, Pile No. 1

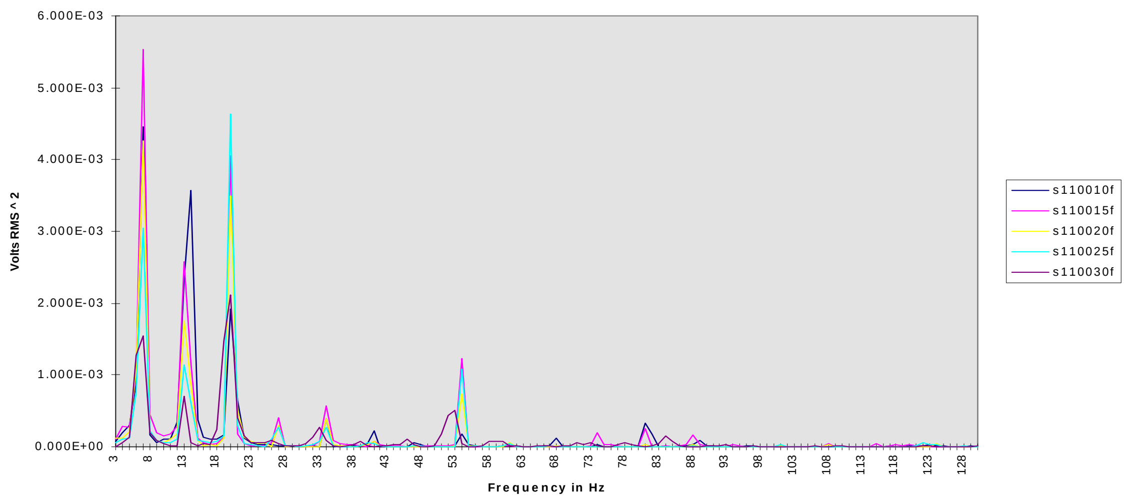


Figure 3: Time Domain Signal, Vibratory Pile Driving, Pile No. 1, Sample T110015

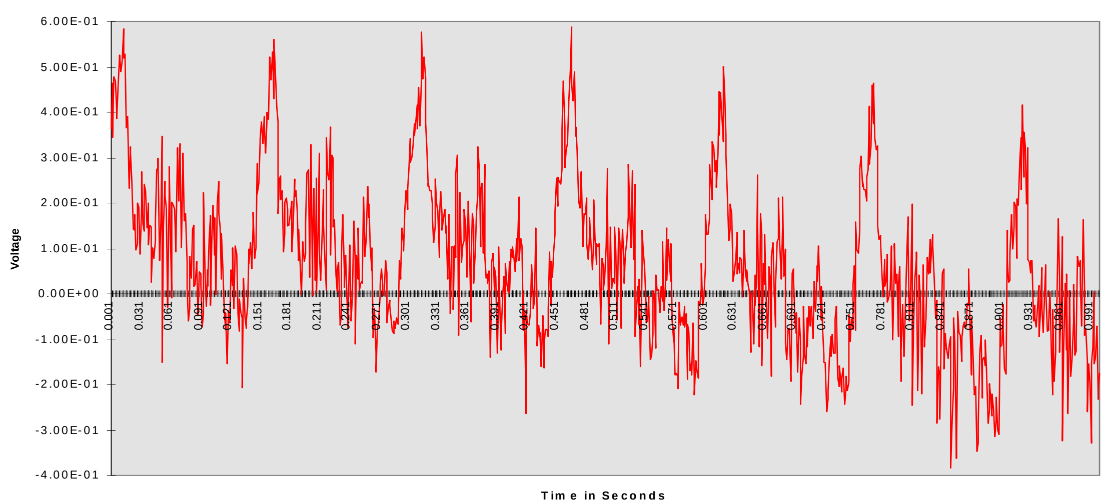


Figure 4: Average Underwater Sound Power Spectrum, Vibratory Pile Driving, Pile No. 2

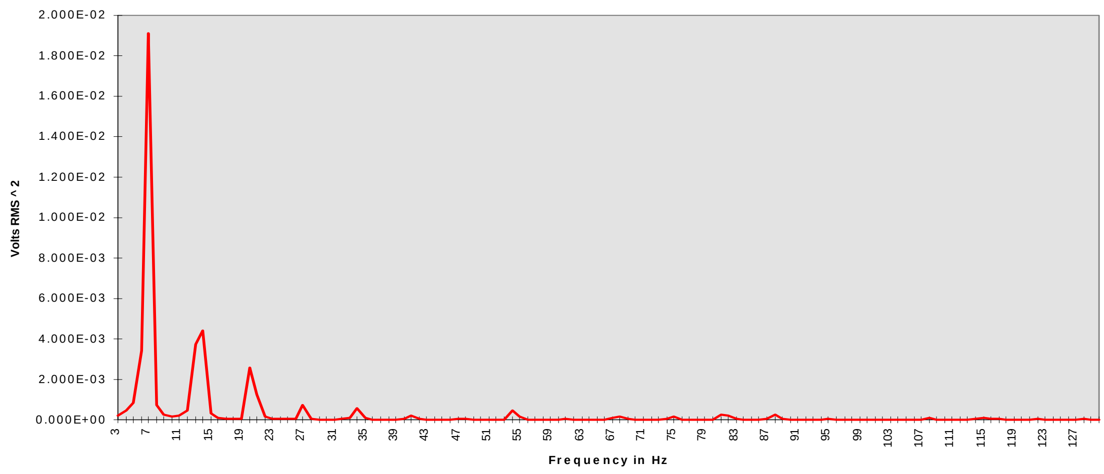


Figure 5: Individual Underwater Sound Power Spectra, Vibratory Pile Driving, Pile No. 2

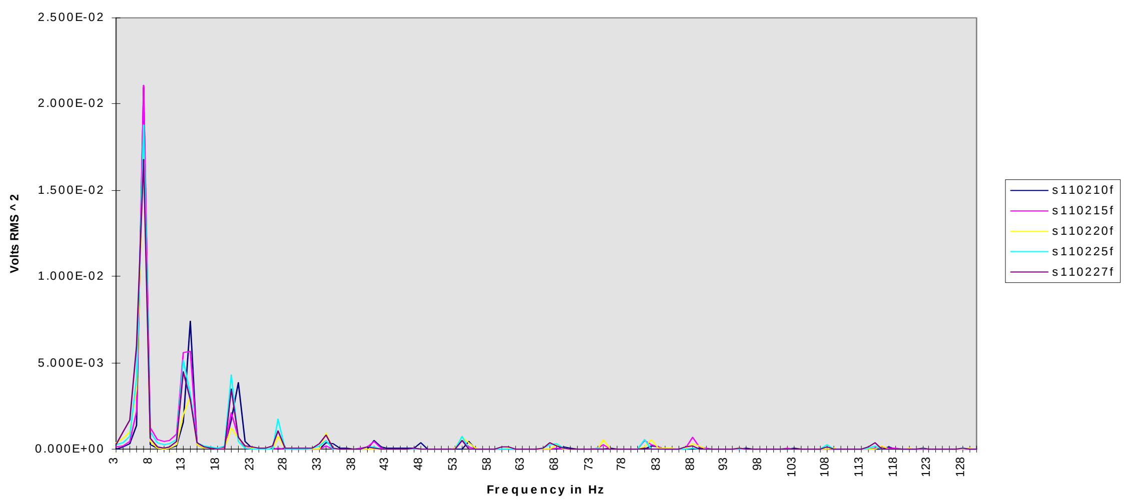


Figure 6: Time Domain Signal, Vibratory Pile Driving, Pile No. 2, Sample T110215

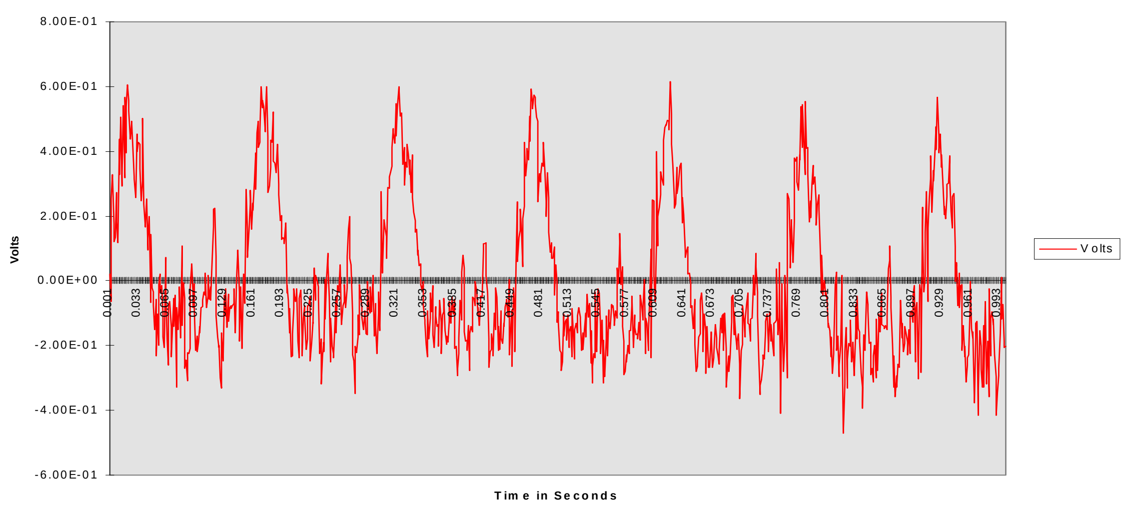


Figure 7: Average Underwater Sound Power Spectrum, Vibratory Pile Driving, Pile No. 3

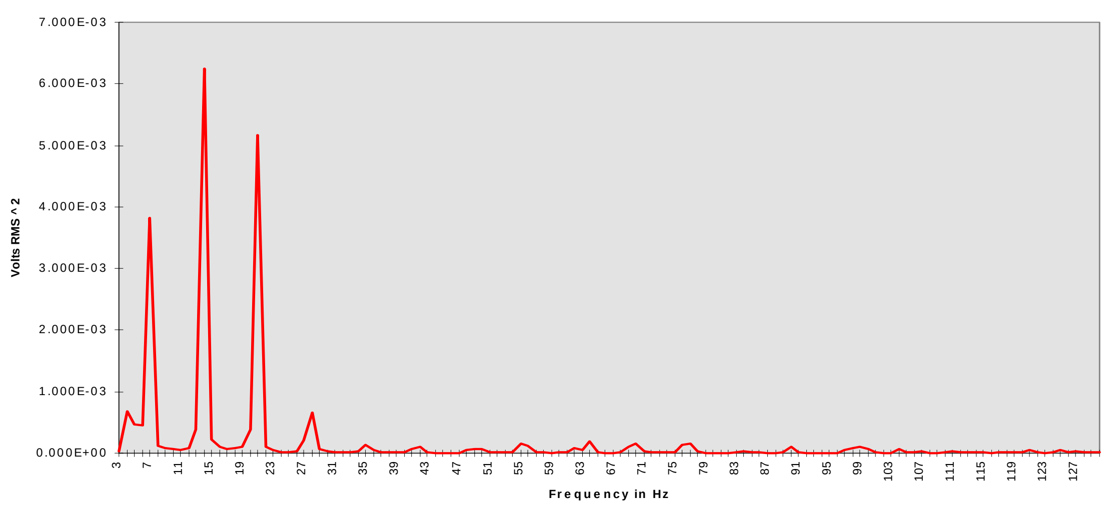


Figure 8: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 3

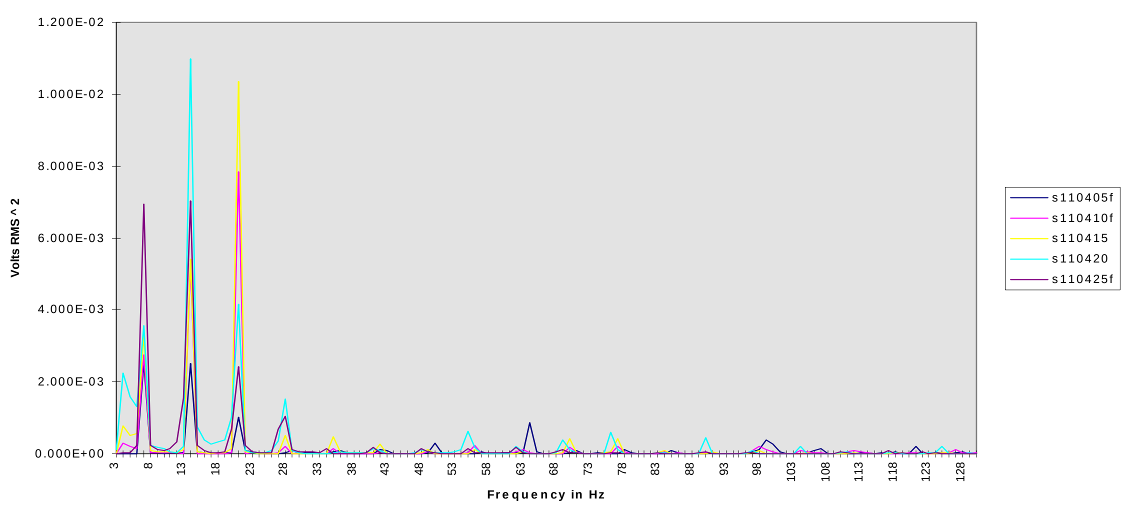
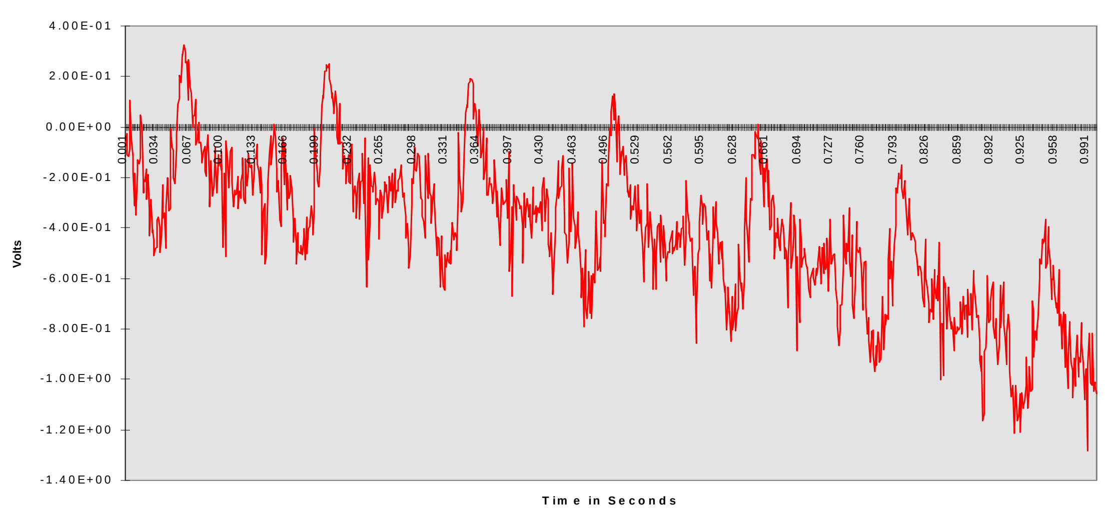


Figure 9: Time Domain Signal, Vibratory Pile Driving, Pile No. 3, Sample T110420



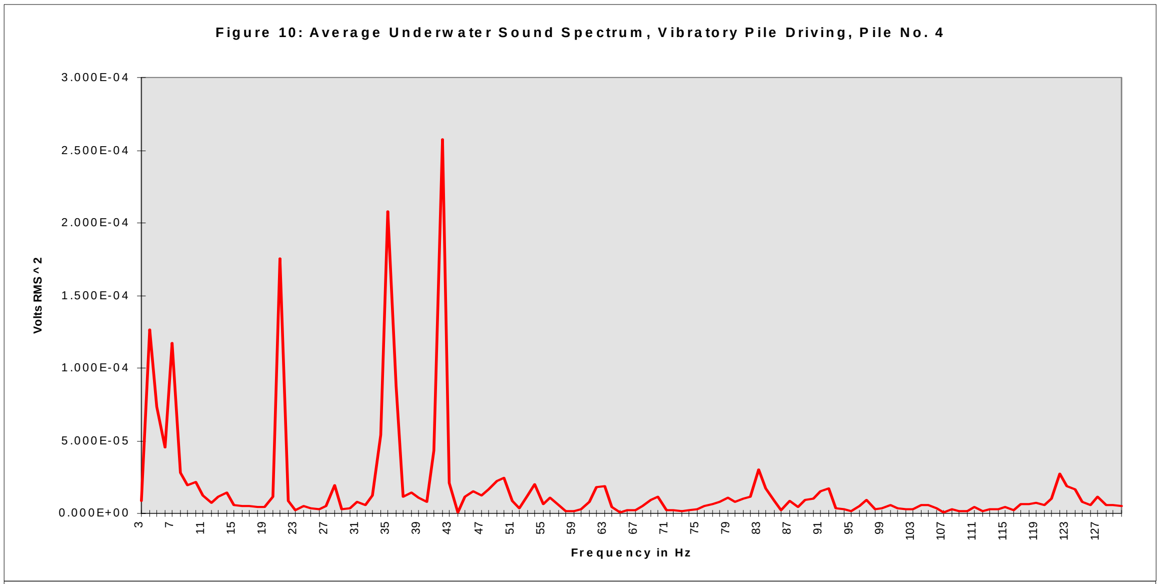


Figure 10: Average Underwater Sound Spectrum, Vibratory Pile Driving, Pile No. 4
Volts RMS ^ 2
Frequency in Hz

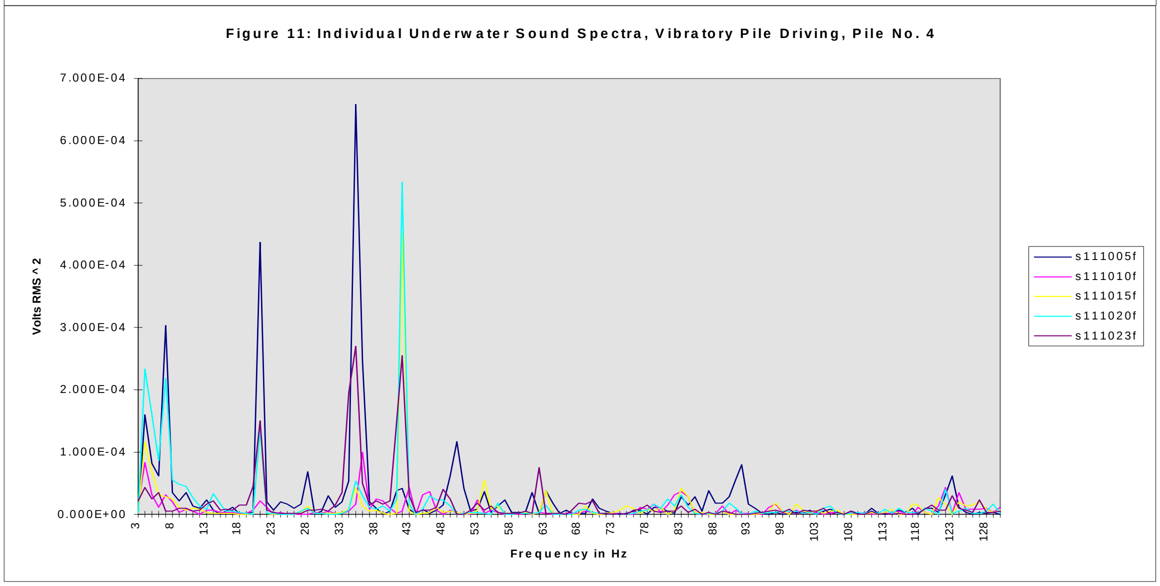


Figure 11: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 4
Volts RMS ^ 2
Frequency in Hz
s111005f
s111010f
s111015f
s111020f
s111023f

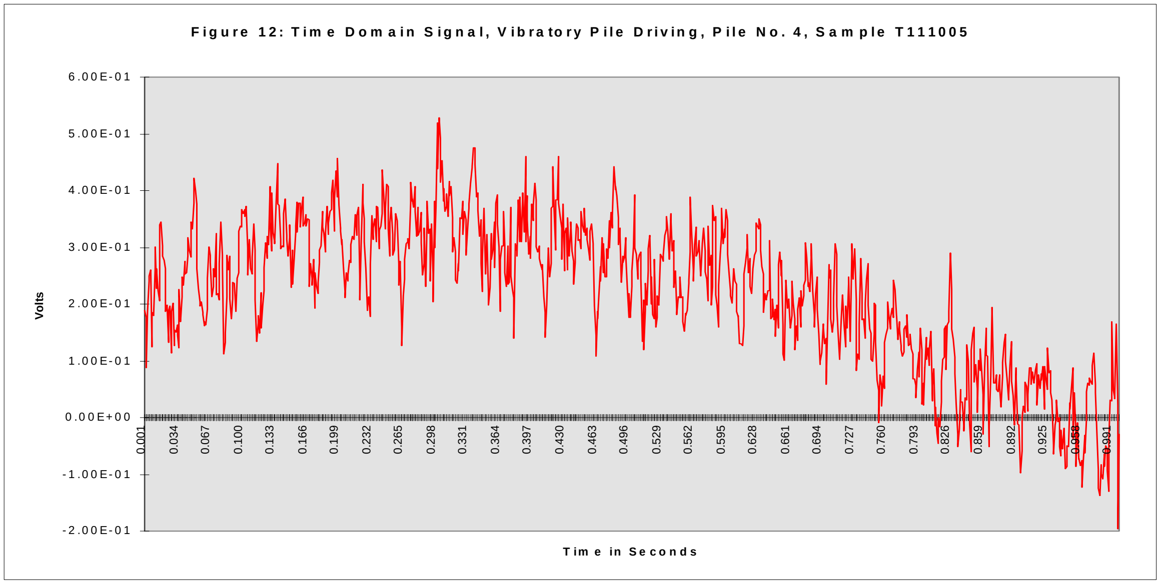


Figure 12: Time Domain Signal, Vibratory Pile Driving, Pile No. 4, Sample T111005
Volts
Time in Seconds
6.00E-01
5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
-1.00E-01
-2.00E-01
0.001
0.034
0.067
0.100
0.133
0.166
0.199
0.232
0.265
0.298
0.331
0.364
0.397
0.430
0.463
0.496
0.529
0.562
0.595
0.628
0.661
0.694
0.727
0.760
0.793
0.826
0.859
0.892
0.925
0.958
0.991

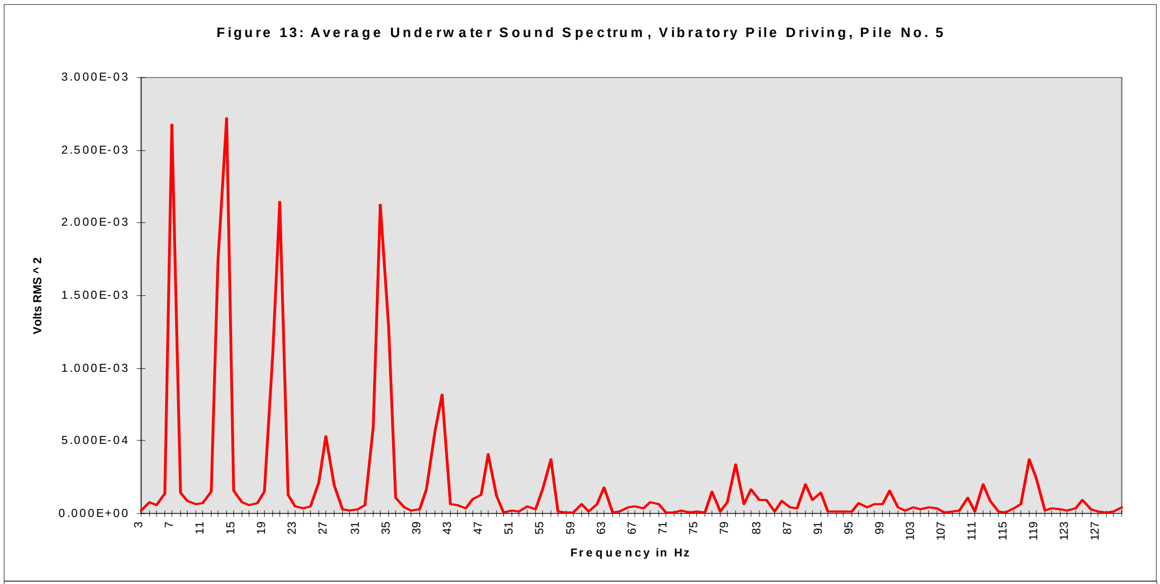


Figure 13: Average Underwater Sound Spectrum, Vibratory Pile Driving, Pile No. 5
Volts RMS ^ 2
Frequency in Hz

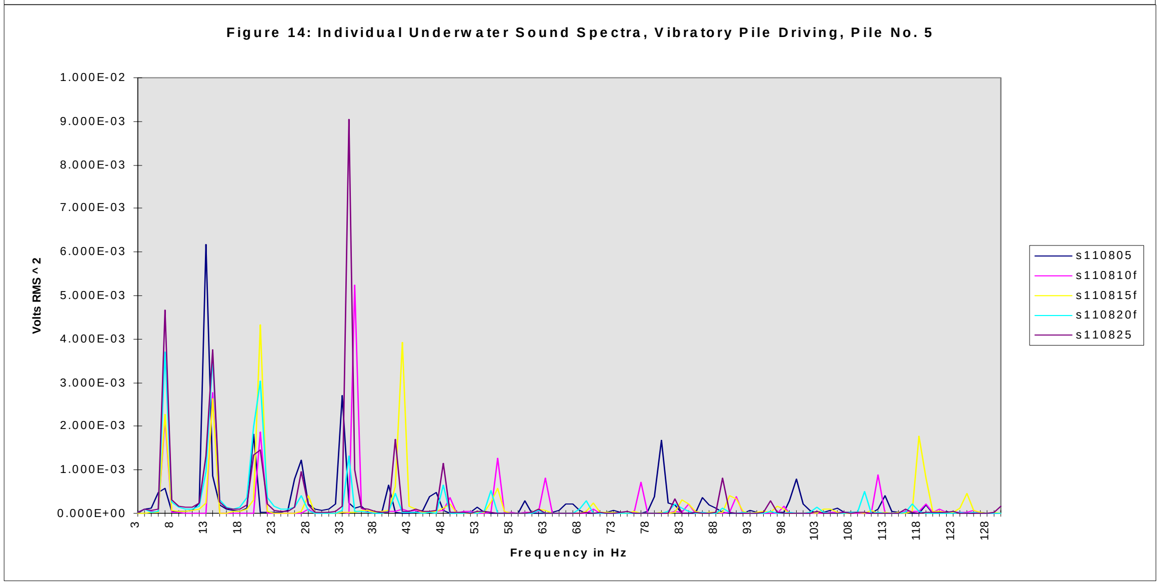


Figure 14: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 5
Volts RMS ^ 2
Frequency in Hz
s110805
s110810f
s110815f
s110820f
s110825

Figure 15: Time Domain Signal, Vibratory Pile Driving, Pile No. 5, Sample T110810

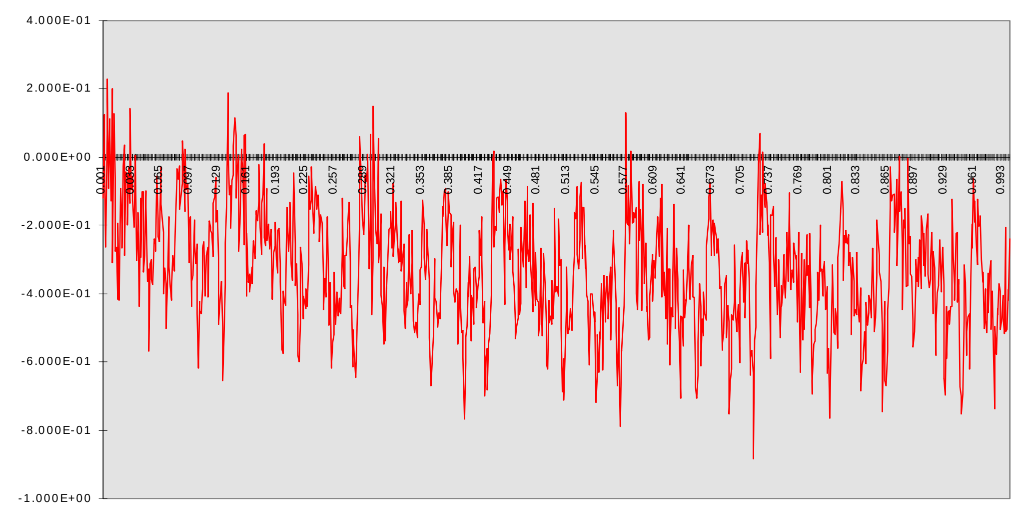


Figure 16: Average Underwater Sound Spectrum, Vibratory Pile Driving, Pile No. 6

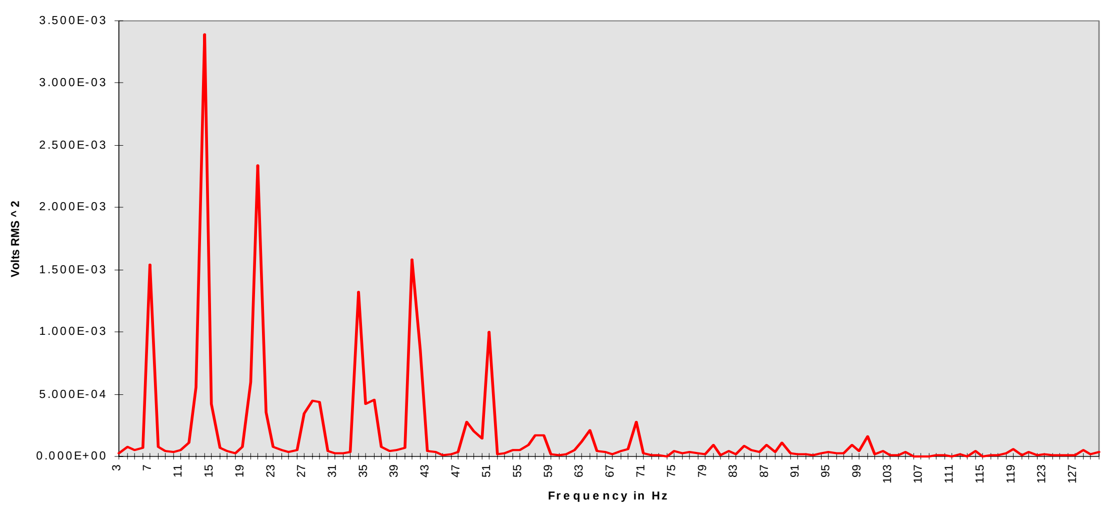


Figure 17: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 6

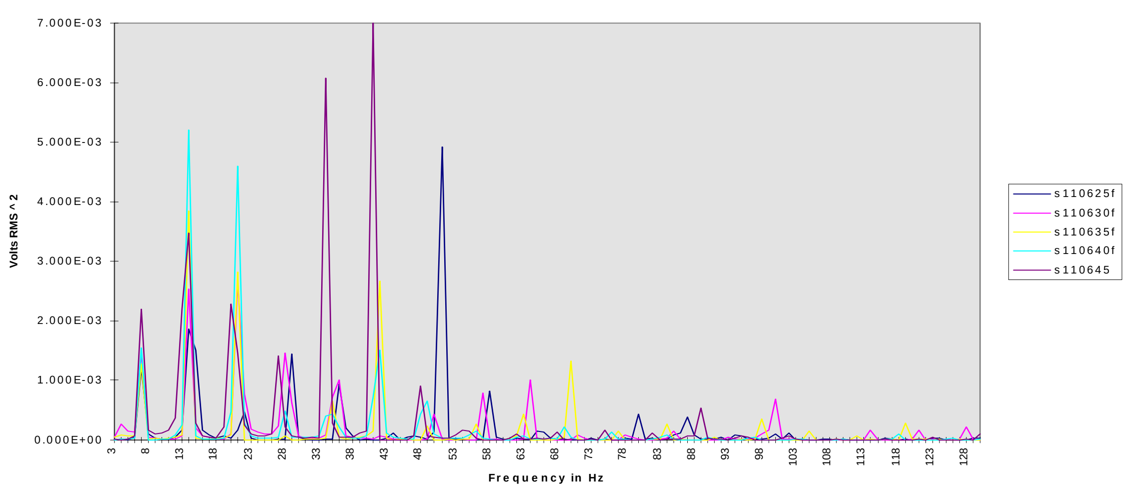


Figure 18: Time Domain Signal, Vibratory Pile Driving, Pile No. 6, Sample T110630

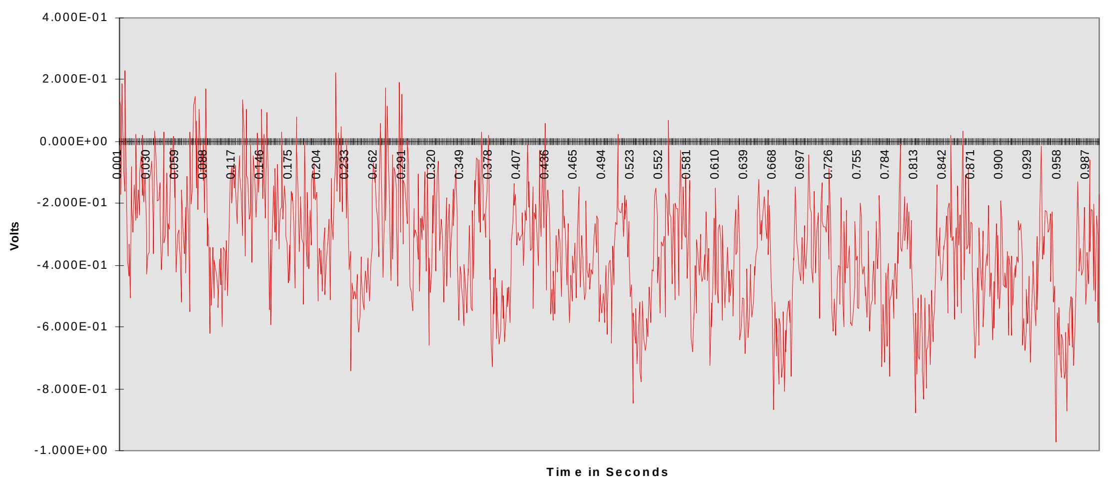


Figure 19: Underwater Sound Power Spectrum, Volume Displacement Infrasound Source

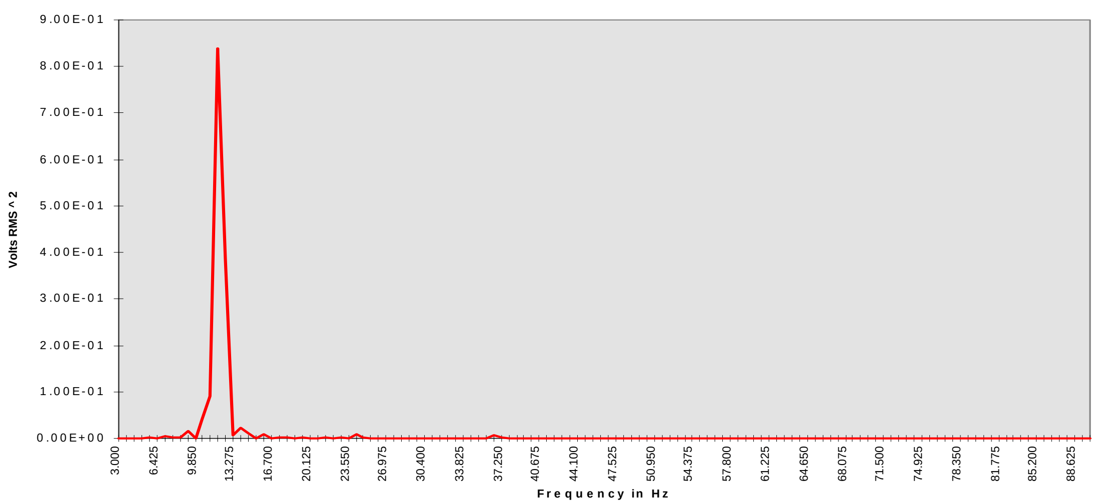
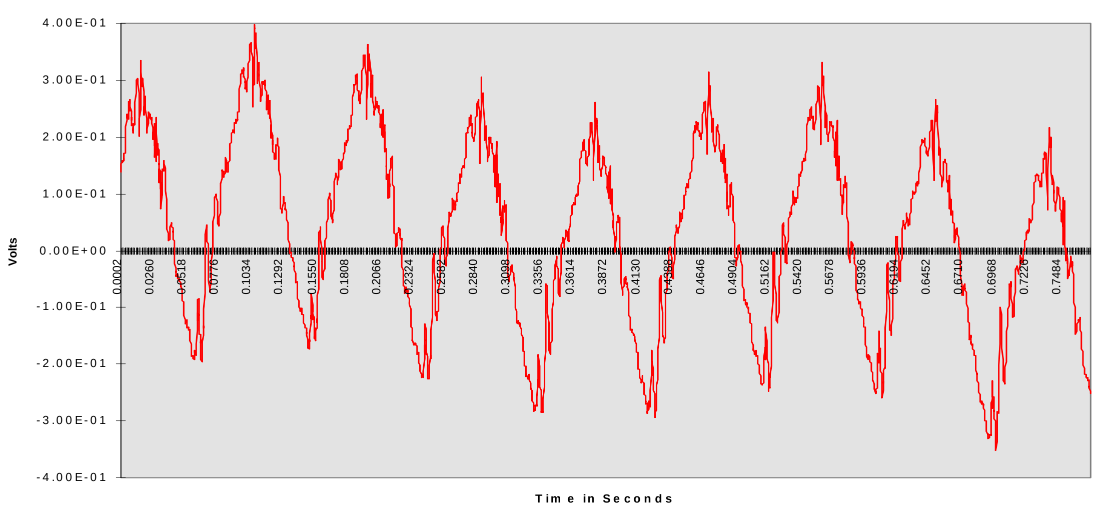


Figure 20: Time Domain Signal, Volume Displacement Infrasound Source



Appendix B

Turbidity Monitoring, Beach Nourishment
Miller Sands, July 20, 1994

Appendix B

Turbidity Monitoring, Beach Nourishment Miller Sands, July 20, 1994[a]

Field data collection of turbidity levels associated with a beach nourishment project was conducted on July 20, 1994, at Miller Sands. Samples were collected at the water surface, at a depth of 5 feet, and at a depth of 15 feet. A continuous roller pump was used to pump water from the various water depths. Individual samples were collected from the pump discharger tube. Turbidity measurements were recorded using a battery-operated ICM (Industrial Chemical Measurement) model 11520 turbidimeter. Samples at the surface and at 5 feet were collected while underway. To collect water from the 15-foot sampling depth the boat had to be stopped, resulting in fewer samples collected at this depth. Data is presented on the attached spreadsheet.

The sample boat was a 20-foot jetsled with a 115hp Mercury outboard that was launched at Tongue Point. Sample collection was conducted under flood tidal flow. The beach was being built in the downstream direction in the opposite direction of the flow at the time of sampling. Material was being actively discharged when we arrived at the outfall and continued unbroken during sample collection.

A turbidity plume was visible extending upstream from the discharge point closely following the shore. Samples were, therefore, collected parallel to shore at a distance of approximately 50 feet offshore. The background turbidity sample was collected downstream and offshore from the discharge point. A sample was also collected directly in front of the discharge point in the embayment created by the beach fill operation. This area had the highest turbidity because of limited mixing. Near the discharge point the turbidity became patchy as the discharge water mixed with the ambient river water. The plume became more uniform further from the discharge point, as reflected by the data.

Time and GPS position readings were recorded along with each turbidity reading. The GPS output was to the nearest second of latitude and longitude and was not differentiated (corrected) to a known position. One second of latitude is approximately 101 feet, while one second of longitude is 70 feet at latitude 46° 15' 22". In addition, weather, wave, and flow conditions did not permit landing of the boat so that a known shore position reading could be taken. Therefore plotted GPS positions can only show relative positions of sample locations to the nearest second. Sample locations are plotted without any adjustment or corrections.

Maximum air temperature conditions were 64°F in Astoria and 104°F in Portland for the day. Winds were from the west up the estuary at more than 25 knots (estimated). In unprotected areas seas were up to 3 feet and mixed in direction but generally up-river. Because of increasing winds and wave conditions monitoring was limited for safety considerations.

(a) This field report was prepared by the U.S. Army Corps of Engineers – Portland District.

The turbidity measurements collected and presented here are considered to be representative of the turbidity at the time and conditions under which the measurements were taken.

Background turbidity was 5.0. Maximum turbidity was 13.9 at the surface, 15.7 at 5 feet, and 16.9 at 15 feet in the discharge plume. A maximum reading of 25.8 was recorded in front of the discharge in the notch created by the advancing fill. Directly offshore of the discharge point the turbidity was patchy due to mixing of the ambient river water with the discharge water.

Table B.1 Turbidity Monitoring at Miller Sands, July 20, 1994

Station No.	Latitude	Longitude	Reading	Time	Comments
Run number 1 (Samples were taken from the water surface approximately 50 feet off-shore)					
1	46 15 10	123 38 25	12.7	11:15	Start of Run.
2			11.6	11:16	
3	46 15 15	123 38 27	11.5	11:16	
4	46 15 16	123 38 29	10.8	11:16	
5	46 15 16	123 38 31	9.9	11:17	
6	46 15 16	123 38 33	10.9	11:17	
7	46 15 17	123 38 35	10.2	11:18	
8	46 15 17	123 38 37	14.0	11:19	
9	46 15 17	123 38 37	10.4	11:19	
10	46 15 18	123 38 38	13.9	11:19	
11	46 15 18	123 38 39	10.6	11:19	
12	46 15 19	123 38 39	13.7	11:20	
13	46 15 19	123 38 40	9.9		
14	46 15 19	123 38 42	19.8	11:22	?? reading may be in error due to water droplet on lens of instrument.
15			8.3	11:22	Patchy turbidity where discharge is mixing with the ambient river water.
16	46 15 19	123 38 45	7.7	11:23	Location is directly off-shore of the discharge point
17	46 15 20	123 38 45	7.5	11:24	
18	46 15 20	123 38 46	5.3	11:24	End of Run
Run number 2 (Samples were taken from 5 feet below the water surface approx 50 feet off-shore)					
1	46 15 13	123 38 25	7.4	11:34	Start of Run.
2	46 15 14	123 38 28	9.2	11:35	
3	46 15 14	123 38 28	10.3	11:36	
4	46 15 15	123 38 29	8.5	11:36	
5	46 15 16	123 38 31	8.6	11:37	
6	46 15 17	123 38 32	10.4	11:37	
7	46 15 17	123 38 33	10.4	11:37	
8	46 15 18	123 38 35	10.6	11:38	
9	46 15 19	123 38 35	12.6	11:38	
10	46 15 19	123 38 37	15.7	11:39	

Station No.	**Latitude**	**Longitude**	**Reading**	**Time**	**Comments**
11	46 15 20	123 38 39	15.1	11:39	
12	46 15 21	123 38 40	14.3	11:40	Patchy turbidity at point of discharge
13	46 15 22	123 38 40	11.9	11:40	
14			6.8	11:41	
15	46 15 22	123 38 41	5.1	11:42	
16	46 15 24	123 38 42	4.4	11:43	End of Run
Run number 3. (Samples were taken from 15 feet below the water surface approximately 50 feet off-shore. Had to stop boat to ensure 15-foot sample point. This decreased the number of samples taken.)					
1	46 15 15	123 38 29	7.0		Start of Run.
2	46 15 15	123 38 28	9.5	11:53	
3	46 15 16	123 38 30	9.6	11:54	
4	46 15 19	123 38 37	16.9	11:57	
5	46 15 20	123 38 41	4.6	11:59	End of run. Patchy turbidity at point of discharge
Miscellaneous Measurements					
Out-fall	46 15 22	123 38 46			
Background			5.0	10.58	Sample taken at 5 feet depth
Plume			25.8		Sample taken from embayment created by beach fill operation