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Project Officers Report—Project 1.3b

Effects of an Underwater Nuclear Explosion on Hydroacoustic Systems

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The objectives of Project 1.2 were to determine and evaluate the effects of an underwater nuclear explosion on the operational capabilities of shipboard sonar and other types of hydro-acoustic systems. Project 1.3b included all measurements at ranges greater than 10 nautical miles and the results of these measurements constitute the subject of this report. This report concerns the effects of the underwater nuclear explosion, Sword Fish, on: (a) Long-range active detection systems at the first convergence zone (25 to 30 miles); (b) Passive shipboard or submarine sonars at a few hundred miles; and (c) Long-range passive detection and surveillance at Sound Surveillance System (SOSUS) and Missile Impact Locating System (MILS) stations at several hundred to several thousand miles.

A submarine station at the first convergence zone and five shipboard stations at ranges from 200 miles to 5,000 miles recorded signals from hydrophones suspended at various depths to approximately 2,000 feet. Submarines on other assignments recorded signals on standard sub-

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marine sonar equipment on a not-to- interfere basis. SOSUS and MILS stations operated normally during the period and also made special magnetic-tape and strip-chart recordings of signals from single hydrophones from before burst time to several hours after burst.

FOREWORD

Classified material has been removed in order to make the information available on an unclassified, open publication basis, to any interested parties. The effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

The material which has been deleted is either currently classified as Restricted Data or Formerly Restricted Data under the provisions of the Atomic Energy Act of 1954 (as amended), or is National Security Information, or has been determined to be critical military information which could reveal system or equipment vulnerabilities and is, therefore, not appropriate for open publication.

The Defense Nuclear Agency (DNA) believes that though all classified material has been deleted, the report accurately portrays the contents of the original. DNA also believes that the deleted material is of little or no significance to studies into the amounts, or types, of radiation received by any individuals during the atmospheric nuclear test program.

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ABSTRACT

The objectives of Project 1.3 were to determine and evaluate the effects of an underwater nuclear explosion on the operational capabilities of shipboard sonar and other types of hydroacoustic systems. (The effects on shipboard sonars at close range were reported under Project 1.3a). Project 1.3b included all measurements at ranges greater than 10 nautical miles and the results of these measurements constitute the subject of this report.

Specifically, this report concerns the effects of the underwater nuclear explosion, Sword Fish, on:

a. Long-range active detection (Lorad) systems at the first convergence zone (25 to 30 miles).

b. Passive shipboard or submarine sonars at a few hundred miles.

c. Long-range passive detection and surveillance at Sound Surveillance System (SOSUS) and Missile Impact Locating System (MILS) stations at several hundred to several thousand miles.

A submarine station at the first convergence zone and five shipboard stations at ranges from 200 miles to 5,000 miles recorded signals from hydrophones suspended at various depths to approximately 2,000 feet. Submarines on other assignments recorded signals on standard submarine sonar equipment on a not-to-interfere basis. SOSUS and MILS stations operated normally during the period and also made special magnetic-tape and strip-chart recordings of signals from single hydrophones from before burst time to several hours after burst.

Although the station at the first convergence zone was not at the proper range to make measurements in the region of greatest pressure, where pressures of the order of 300 psi were considered possible, peak pressures up to were recorded. Under isovelocity conditions, peak pressures of the order of would have been expected. Thus, the convergence-zone pressures may be considerably larger than would be expected without refraction, but the magnitude of the possible threat to equipment operating in the convergence zone has not been positively determined.

For shipboard or submarine sonar systems operating within a few hundred miles of the burst, the effect of the burst This result would be expected from the fact that the background noise in these systems is normally much higher than for land-based stations and thus they are limited to higher signal levels. Although some masking of ships' signals received on shipboard stations operating within several hundred miles of a nuclear explosion in the open ocean must be expected, the duration of such masking should be limited to a very few minutes.

PREFACE

Shot Sword Fish was an underwater weapon-effects test conducted in the Pacific Ocean off the southwest coast of the United States in May 1962 as part of Operation Dominic. Sword Fish was the first fully operational test of the Navy's antisubmarine rocket (ASROC) weapon system in which a nuclear war reserve weapon was expended. Weapons-effects information of importance to the advancement of surface-ship capability to conduct nuclear antisubmarine warfare was obtained. An overall description of the test efforts and a summary of preliminary results may be found in the Sword Fish Scientific Director's Summary Report, which includes general information such as location and time of burst. A guide to Sword Fish Reports is included.

This report concerns the effects of the underwater nuclear explosion, Shot Sword Fish of Operation Dominic, on the operation of hydroacoustic systems at long range (several miles to several thousand miles) from the burst. (The effects on shipboard sonar systems in the immediate vicinity of the burst were reported separately under Project 1.3a.)

This project was strongly dependent on data from other sources. The Pacific Missile Range MILS stations and the Western Sea Frontier SOSUS stations made special recordings of the signals from this test. In addition, recordings were made by a number of submarines of the Pacific Fleet. The valuable contributions made by all these agencies are gratefully acknowledged.

Although gathered primarily for another project, valuable data for this project were obtained from shipboard measurements at several widely separated locations. The ships involved in these measurements were the USS ARIKARA (ATF-98), the USS GANNET

(MSC-290), the USS LIPAN (ATF-85), the USS SEA FOX (SSG-402), the USS TAWAKONI (ATF-114)

The cooperation and support of the officers and crews of all of these ships were outstanding and were largely responsible for making these measurements possible. This willing support and assistance are gratefully acknowledged.

The detailed description of the effects of Sword Fish on the operational capabilities of the SOSUS stations is based largely on an analysis of the Lofargrams made by Mr. Robert Guariglia of the Naval Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, whose contribution is greatly appreciated.

The authors wish to acknowledge the invaluable assistance of Helen M. Blanchard who not only did a large amount of the data reduction but who prepared all the figures for this report.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

The basic objective of Project 1.3 was to determine and evaluate the effects of an underwater nuclear explosion on the operational capabilities of shipboard sonar and other types of hydroacoustic systems, including:

a. Operational sonars, with operating frequencies of 5 to 12 kc/s, on surface ships and submarines operating within 10 miles of the burst.

b. Convergence zone, Long Range Active Detection (Lorad) type, submarine sonar systems operating at ranges of 25 to 30 miles.

c. Long-range, passive, bottom-mounted hydroacoustic detection systems of the Sound Surveillance System (SOSUS) type at ranges of several hundred miles from the burst.

To simplify administration and reporting, Project 1.3 was subdivided into Projects 1.3a and 1.3b. Project 1.3a encompassed all measurements on shipboard and submarine sonars at ranges less than 10 miles (objective a above) and is covered in Reference 1. Project 1.3b included all measurements at ranges greater than 10 miles (objectives b and c above), and is the subject of this report.

During the preparation phase for the Sword Fish test, some uncertainty arose as to the complete safety of the Lorad transducer and possibly other parts of the Lorad system operating submerged at the first convergence zone. Because of this uncertainty, the original objective of determining the effects of the burst on the operation of the Lorad system under realistic operating conditions had to be abandoned. However, this same uncertainty emphasized the importance of determining the pressure field to be expected at convergence-zone range and the project objectives were modified accordingly.

The specific objectives of Project 1.3b, as conducted, were to:

a. Determine the amplitude and characteristics of the shock wave from an underwater explosion as a function of depth in the region near the first convergence zone (25 to 30 miles in the test area) to evaluate the possible danger to a submerged submarine or its equipment under Lorad operating conditions in a nuclear warfare environment.

b. Determine the pressure-time field as a function of depth in open water at ranges from 200 miles to several thousand miles to permit prediction of possible masking effects of these signals on hydroacoustic systems.

c. Determine the effects of the burst on the operational capabilities of long-range, bottom-mounted, passive detection systems of the SOSUS type under standard operating conditions.

d. Determine the signal and reverberation pressure levels as a function of time for several hours after the burst at all available land-based stations (SOSUS and Missile Impact Locating System (MILS) stations) to evaluate the effectiveness of these signals in masking normal submarine-generated signals.

e. Obtain qualitative information, on a not-to-interfere basis, from submarines operating within a few thousand miles of the test area to determine, in a very general manner, the effects which might be encountered at long ranges in a nuclear warfare environment.

1.2 BACKGROUND AND THEORY

Prior to the Wigwam test in 1955 there was little interest in the effects of nuclear explosions on hydroacoustic systems.

Also, measurements made at the Pacific sofar stations (Reference 2) showed that the high signal level from the burst

Consequently, interest in the effects of nuclear explosions on hydroacoustic systems greatly increased, and several analytical and experimental investigations of the problem were initiated (see Reference 3). Incomplete results of these investigations showed that indeed there were conditions under which

The generation of shock waves by a chemical explosion in the water is quite well understood (Reference 4). Measurements, at short ranges, of the shock waves produced by underwater nuclear explosions have been made by a number of agencies (see References 5 through 8), and limited studies of the propagation of these signals to ranges of a few thousand feet in a variable-velocity medium and in the vicinity of boundaries have been conducted, as reported in References 9 and 10.

Although considerable information is available on convergence-zone propagation of relatively high-frequency, low-amplitude, sinusoidal waves (see References 11 and 12), convergence-zone propagation of shock-wave signals has not been as thoroughly investigated. It is to be expected that the propagation of signals from a large explosion might not be the same as the propagation of high-frequency transducer-generated sinusoidal waves. For example, during the preparation of Reference 10, it was found that the Hardtack Wahoo burst could not be considered as a point source in connection with propagation to ranges of 9000 feet. These results indicated that, for energy propagated above the thermocline, a source depth well above the thermocline appeared appropriate, whereas, for deeper propagation the source appeared to be below the thermocline. Thus propagation to the first convergence zone is not completely predictable.

Several years of experience with Lorad propagation studies have shown that, under certain conditions, with source and receiver both near the surface, the signal at the convergence zone may be as much as 26 decibels stronger than would be expected under isovelocity conditions.

If it is assumed that the familiar equation from Reference 4,

$$P_{max} = 2.16 \times 10^4 \left[\frac{W^{1/3}}{R}\right]^{1.13} \text{ psi}$$

(for W pounds of TNT at a range of R feet), is valid for isovelocity conditions to ranges of 25 to 30 miles, then the peak pressure level which might have been expected at this range in the absence of refraction can be calculated. The radiochemical yield of the Sword Fish burst was reported in Reference 13 as

References 5 and 14 state that the TNT equivalent yield of an underwater nuclear explosion is about

of the radiochemical yield. Thus, the TNT equivalent charge weight for Sword Fish is about

Based on the sound-velocity conditions existing at test time, the calculated range from the Sword Fish burst (at a depth of 670 feet) to the first convergence zone (at the same depth) is 25.5 nautical miles or approximately 155,000 feet. Thus, under isovelocity conditions, the peak pressure should be

If this hypothetical signal is increased by due to refraction, then the resulting peak-pressure level would be

A pressure level of this magnitude

Furthermore, it must be remembered that this value is somewhat speculative; the peak pressure might be considerably larger.

Even after the question of equipment safety in the first convergence zone is answered, some basic questions related to active probing of the convergence zone by a Lorad-equipped submarine still remain. For example: Will echoes from a target submarine at the first convergence zone be masked by the high noise level (reverberation, etc.) immediately following an underwater nuclear burst and, if so, for what period of time? What is the extent, duration, and effectiveness of the turbulent area immediately surrounding an underwater nuclear burst in screening a target behind the burst site from a Lorad-type system operating in the first convergence zone? What is the dependence of any such screening effect on time, signal frequency, yield, burst depth, water depth, etc.? Some of these questions can be answered only by placing an operating Lorad system at the burst depth in the first convergence zone and tracking a target behind the burst,

Long-range, deep-water propagation of low-frequency hydro-acoustic signals from small explosions deep in the ocean has been understood for many years (see Reference 15). A great deal of work on sofar-type propagation (reported in Reference 16) has determined some of the parameters affecting the transmission of such signals. It has been found, for example, that a source off the axis of the deep sound channel produces less signal at long ranges than does the same source on the axis. Islands and sea-mounts which partially obstruct signal paths have been found to greatly attenuate these signals. Work with underwater explosions, both chemical and nuclear, has resulted in a reasonably good understanding of shock waves at short range as a function of time. The effects of refraction on the propagation of shock waves to ranges of a few thousand feet in deep water have been studied (References 9 and 10), and the effects of islands, sea-mounts, and other shallow-water areas on the propagation of shock waves from large chemical explosions in shallow water have been measured (Reference 17). However, there are still many uncertainties concerning the propagation of such signals under less than ideal conditions and an understanding of propagation phenomena is essential to effective evaluation or prediction of the effects of an underwater nuclear burst on various types of hydroacoustic systems. Even the peak-pressure levels at ranges of a few hundred miles from a large nuclear burst in deep open water are not known with certainty, since such measurements have never been made. The Wigwam test in 1955 and the Wahoo test of Operation Hardtack in 1958 (the only deep underwater nuclear tests conducted by the United States prior to Sword Fish) were not instrumented to study propagation to these ranges. Such information is of great importance for understanding and predicting the capabilities of various types of hydroacoustic systems in a nuclear warfare environment.

Land-based long-range hydroacoustic detection systems, both active and passive, depend upon very low level hydroacoustic signals for providing information on submarines operating in their general area. A very low ambient-noise level is essential for effective operation of such systems. Following the Wigwam burst

CHAPTER 2

PROCEDURE

2.1 GENERAL

Since the purpose of this project was to study the effects of the Sword Fish burst on the operation of several types of hydroacoustic systems at ranges from a few miles to several thousand miles from the burst, a very large number of measuring stations was required. Therefore, in addition to the one submarine and five surface ships on which special monitoring equipment was installed, all available hydroacoustic installations recorded the signals and all submarines operating in the Northeast Pacific Ocean were asked to monitor on a not-to-interfere basis.

The Sword Fish burst occurred at 31°14.7'N, 124°12.7'W, approximately 270 miles southwest of Point Conception, California. The locations of the various types of off-site monitoring stations and of the burst point are shown in Figure 2.1.

The instrumentation at the different sites varied greatly; therefore, each type of monitoring station will be discussed separately.

2.2 USS SEA FOX (SSG-402)

A very few days before the scheduled firing date for Sword Fish, the submarine SEA FOX was made available for measurements at the first convergence zone. Such equipment as could be made available was hurriedly installed and the SEA FOX took up her station near the estimated range for the first convergence zone. She was positioned on the surface, with her bow submerged, and 4 hydrophones were suspended to depths of 150, 400, 700, and 1,000 feet. Three Research Manufacturing Company (Remaco) R-101 hydrophones and one 14D3X hydrophone were used. Signals were recorded on a 14-channel Minneapolis-Honeywell Visicorder at a paper speed of 5 inches per second. To ensure recording at the correct amplitude, the output of each hydrophone was recorded at two different sensitivities. In addition, the signal from the deepest hydrophone was recorded at a still greater sensitivity to permit recording of reverberation levels after the main shock wave had passed.

2.3 USS GANNET (MSC-290)

To determine some of the characteristics of the sound field in deep open water, the GANNET was located 198 miles southeast of the burst, at 28°9'N, 122°45'W, where the water depth is 2,000 fathoms. Six Remaco R-101 barium titanate hydrophones were suspended from the ship to depths of 150, 400, 750, 1,100, 1,500, and 2,000 feet. The output of each hydrophone was recorded at two different levels on a 14-channel Ampex tape recorder, with five-second timing signals recorded on one channel and timing signals from radio station WWV on another. The recording speed was 15 inches per second and the recorder was operated from H-30 minutes to H+4 hours, with short interruptions to change reels of tape.

2.4 SHIP STATIONS AT LONG RANGE

Three ships in the Hawaiian area and

were used as monitoring stations. The USS TAWAKONI (ATF-114) was located about 250 nautical miles northeast of the island of Oahu, the USS ARIKARA (ATF-98) operated about 150 miles west-southwest of the island of Hawaii, the USS LIPAN (ATF-85) was approximately 650 miles west-southwest of Hawaii,

The monitoring equipment on these ships was the same as that described previously for the GANNET, but of course the gain settings were different.

Since the primary purpose of these stations was to obtain information for another project on the detection of nuclear explosions (Reference 18), some of the locations were not optimum for studying the effects of nuclear explosions on hydroacoustic systems at long ranges.

2.5 WESTERN SEA FRONTIER SOSUS STATIONS

For this test the outputs of two or more hydrophones were recorded separately (and without processing) on a magnetic-tape recorder and on a Sanborn strip-chart recorder. At most stations these recordings were made from H-30 minutes to approximately H+8 hours. In addition to these records, the Lofar recorders were also in continuous operation in the normal manner and the Lofargrams were made available for study.

2.6 PACIFIC MISSILE RANGE MILS STATIONS

The Pacific Missile Range MILS stations

After amplification ashore, the data was recorded on magnetic tape and on Sanborn strip-chart recorders. The equipment was operated from H-30 minutes to H+8 hours.

2.7 FLEET SUBMARINES AT VARIOUS LOCATIONS

To obtain qualitative information on the effects of the nuclear burst on the normal operation of submarine sonar systems, all submarines operating in the Northeast Pacific Ocean were asked to monitor the burst on a not-to-interfere basis. Recordings of the sounds received on the sonar systems and the comments of the sonar operators concerning both these sounds and those heard directly through the ship's hulls were forwarded to the Navy Electronics Laboratory for study.

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CHAPTER 3

RESULTS AND ANALYSIS

3.1 BURST INFORMATION

Information concerning the Sword Fish test (taken from Reference 13) is listed in Table 3.1. The location of the shot point is about 270 nautical miles southwest of Point Conception, California. The locations of the various off-site monitoring stations and the shot point are shown in Figure 2.1.

3.2 EXPECTED SIGNAL LEVELS

A detailed discussion of the expected signal levels will be given in Section 4.1. However, as the peak signal levels observed at different locations will be compared to the expected levels in this chapter, a brief introduction may be helpful. The expected levels were calculated on the basis of measurements of signals from smaller charges (see Reference 20), with equipment covering the band from approximately 20 to 500 cps, and scaled to an effective source strength for Sword Fish of

at a range of 1 yard, over the same band. Based on this source strength for the 20- to 500-cps band, theoretical spectra extending to lower frequencies have been derived for different ranges, taking into account the variation of attenuation with frequency as given in Reference 2. Extension of the spectrum on the low-frequency side to 3 cps increases the wide-band source level by about 7 decibels, giving a source level of

for the 3- to 500-cps band. The

spectra based on this source level and pass band have been used in connection with the MILS and SOSUS hydrophone-response curves to predict the level of the hydrophone output at the different stations.

3.3 USS SEA FOX AT FIRST CONVERGENCE ZONE

The sound-speed profile as measured near the test site shortly before the test and reported in Reference 21, is shown in Figure 3.1. Based on this profile, calculations indicate that the peak of the convergence zone at burst depth will occur at a range of approximately 25.5 nautical miles. A ray diagram based on the above profile and covering the region from 24 to 30.5 nautical miles and depths from the surface to 4000 feet, is shown in Figure 3.2. The concentration of rays at the burst depth at the 25.5-nautical-mile range is striking. (Bottom-reflected rays are not shown in the figure.)

Due to uncertainty in exactly positioning the SEA FOX relative to surface zero and also due to the fact that the near side of the convergence zone is quite sharp, scientists aboard the submarine purposely selected a position at a somewhat greater range. At shot time, the SEA FOX was northwest of the burst, near 31° 38' N, 124° 32' W. The computed range to this location is 28.5 nautical miles, with an estimated accuracy of ± 1 nautical miles.

Countdown information was received by the SEA FOX until the control was transferred from the launch ship to an aircraft, about

2½ minutes before the explosion (Reference 13), but contact was lost at that time and was not regained until -5 seconds. To avoid missing the signal, the Visicorder was started during the period when no countdown was being received, and therefore the record did not continue after the burst as long as was desired, but did continue for approximately 1½ minutes after the first arrival. Portions of the Visicorder record are shown in Figure 3.3. In Figure 3.3(a), the continuous section from 25 seconds before to 12 seconds after the start of the main signal shows the quiet condition of the high-gain channel before the seismic arrivals, the seismic arrivals, and the main part of the signal.

Figure 3.3(b) shows a later section of the record, with a signal which is probably due to a reflection from some seamount, and Figure 3.3(c) shows the end of the Visicorder record. Note that almost 1½ minutes after the main arrival, the signal has still not completely disappeared, as may be seen by comparing the high-gain channel here with the same channel on the first part of Figure 3.3(a). The amplitude of the envelope of the high-gain channel record, shown in Figure 3.4, illustrates the rate of signal decay. Tracings of the Visicorder records of the low-gain channels, showing the main-arrival signals and indicating the peak pressures, are shown in Figure 3.5. A recording was also made from the standard sonar equipment aboard the

SEA FOX. This is shown in Figure 3.6 and shows the reverberations lasting for several minutes. The relatively low gain of even the most sensitive channel on the Visicorder records discussed earlier (Figure 3.4) permitted its recording most of the early portion of the signal which overloaded the sonar record for the first 15 or 20 seconds. This high-gain channel of the Visicorder was read and plotted on a logarithmic scale and is superimposed as a dotted line on the sonar record in Figure 3.6. Aside from the initial signal peaks recorded on the other Visicorder channels, Figure 3.6 gives as complete a picture of the signal level as it is possible to reconstruct from the records.

Levels shown on the figure are from calibrations of the high-gain channel of the Visicorder record.

In an effort to determine the range to the SEA FOX with better accuracy, wave-front patterns were computed at half-mile intervals for several locations about the computed range of 28.5 nautical miles. The patterns were compared with the variations in the arrival times for the different parts of the signal at the four hydrophones (see Figure 3.5) in order to find the location where the expected relative arrival times would agree with the time differences recorded on the SEA FOX. The best agreement was found to be at a range of 28.5 nautical miles, which was the only one giving a reasonable approximation to the observed 70-msec time difference for the main arrivals at the 1000-foot hydrophone. Figure 3.7 shows the expected signals as compared to the received signals at the four hydrophone depths, and Figure 3.8 shows the wave-front pattern at 28.5 nautical miles at a particular time, as well as the position of the hydrophone string required to obtain the expected signals shown in Figure 3.7. It will be noted that in the figure all of the expected signal arrivals are initially positive while the observed signals are both positive and negative. No explanation has been found for the negative signals, since all of the rays, except the few near the surface, are rays which have not been surface-reflected, and hence they would be expected to be positive.

Calculations were made to determine the highest pressures to be expected at different locations within the region covered by the ray diagram of Figure 3.2. At the estimated position of the SEA FOX, at a range of 28.5 nautical miles, the three lower hydrophones are in a region where the peak pressures were computed to be in the range, which is in reasonably good agreement with the observed. The calculations indicate that the shallowest hydrophone, at 150-foot depth, should be in a region of higher pressure, about but the observed peak pressure was As this hydrophone was in a region where positive (non-reflected) rays and negative (surface-reflected) rays would be arriving within very short time intervals, it seems likely that an interference phenomenon may have caused the reduced pressures.

On the basis of the observed pressures alone, it would appear that the SEA FOX was at a range of 29.5 nautical miles. However, since the temporal pattern of the calculated arrivals at 29.5 miles is so different from that observed, while that at 28.5 miles agrees so well with the observed, it is believed that the 28.5-nautical-mile range is correct, even though the observed inversion of some pulses has not been explained.

The SEA FOX at 28.5 nautical miles was three miles beyond the range at which the highest pressures in the convergence zone would have been encountered. Based on the rather good agreement of the computed and measured pressures at the range of the SEA FOX, it appears that the peak pressures in the convergence zone, at a depth of 670 feet, would indeed have exceeded

However, the maximum pressure in most of the region shown in Figure 3.2 is greater than and much of it is greater than

These few measurements in the first convergence zone, while indicative, are certainly not enough to answer the questions of the safety of submarines or transducers operating at such ranges from an underwater nuclear burst. More extensive measurements at several ranges within the convergence zone under well-documented thermal conditions and using either nuclear explosions or fairly large conventional HE charges as sound sources should be made in order to delineate more precisely the pressure fields which occur under these conditions.

3.4 USS GANNET, 198 MILES SOUTHEAST OF THE BURST

Satisfactory signals of the initial shock wave and early reverberations (for approximately 40 seconds) were obtained from the magnetic-tape recordings made aboard the GANNET. At all depths, the peak wide-band signal was about

A tracing of part of the signal from the 1000-foot hydrophone is shown in Figure 3.9, showing a reflection at 2006:50 from Jasper Seamount. The high noise level prevented any late-arriving signals from being observed on the original, wide-band, recordings. When the recordings were played back through third-octave filters, however, reflections from several seamounts, islands, etc., were found. Some of the reflectors identified from later portions of the third-octave filtered records are the United States Coast (at 2013Z), Guadalupe Island (2014Z), Fieberling Seamount (2015Z), and Alijos Rocks (2023Z). Considerably later, at 2118Z, a reflection from Hawaii arrived. Numerous other reflections are present on the records, but their sources have not been identified.

Following the arrival of the initial signal, when the attenuation in the system was reduced, it was found that the wide-band noise level was about 36 decibels re 1 dyne/cm^2. It is assumed that this was also the wide-band noise level before the signal's arrival. This is considerably above what would be expected, and is no doubt due to the fact that the hydrophone string was being dragged through the water by the ship as it drifted with the wind. In addition, this level is above the level of most of the reflected signals received at X-RAY, the SOSUS station at comparable range, and accounts for there being almost no reflected signals observed on the original wide-band records from the GANNET.

Since the filters which brought out the reflected signals covered only frequencies above 80 cps, it appears that most of the noise was in the low-frequency part of the spectrum.

Figure 3.10 shows the record from the GANNET along with the record received at X-RAY. The signal received at the GANNET was passed through a 125-to 158-cps third-octave filter to improve the signal-to-noise ratio. The signal level scale was then set so that the peak of the filtered signal was at the peak of the original signal. Thus, by the filtering process the low-frequency noise was removed, and the reverberation levels were determined. The estimated noise level is indicated, showing that the wide-band level of the signal after the first peak was below the wide-band background-noise level. The method of obtaining the wide-band reverberation levels from readings made with third-octave filtered records assumes that the ratio of energy in the third-octave band to that in the whole spectrum remains the same. This assumption should be reasonably valid for signals recorded more than about 100 miles from the source and for frequencies below 300 cps.

Although the pressure level measured at the GANNET is about 15 decibels lower than the expected level, the reverberation levels at the GANNET agree with those at the SOSUS station. However, as Figure 3.10 shows, the peak level at the GANNET is about 5 decibels lower than at the SOSUS station. Since the bottom depth between the shot point and the GANNET was greater than 2,000 fathoms, there should have been essentially no loss of signal strength due to bottom losses. Another mechanism which might account for the weak signal is that, even at the range of about the sixth convergence zone, there may have been zonal effects present, and that at a range a few miles different, the signal strength might have been much greater. Finally, there might have been an error in system calibrations.

3.5 USS TAWAKONI, 250 MILES NORTHEAST OF OAHU

The locations of the four ship stations at long ranges are given in Table [illegible].2. The TAWAKONI, 1,673 nautical miles from the burst and in open, unobstructed water, received hydroacoustic signals from Sword Fish at about 2036:44Z. At this time, the noise level was high, due to rough seas caused by a storm which was in the vicinity. In addition, the attenuator settings were not optimum for the conditions and thus the dynamic range of the system was limited.

Wide-band signals were from above noise. However, when the tapes were played back through third-octave filters, signals in the bands from 125 to 300 cps were about above the noise level. Thus it appears that, as in the case of the GANNET, most of the background noise was in the low-frequency part of the spectrum. Because of the high noise level, the only reflected signal observed, even on the third-octave records, was the reflection from the Hawaiian Islands.

3.6 USS ARIKARA AND USS LIPAN, WEST-SOUTHWEST OF HAWAII

The primary purpose of these two stations, located 150 and 650 miles west-southwest of Hawaii (1963 and 2435 miles from the burst), was to study the possibility of detecting hydroacoustic signals from underwater nuclear explosions at stations located behind islands; however, the information is of interest to this project. As was anticipated, these stations received much weaker signals than would have been expected at this range in open water. A few weak reflected signals were also received, but the exact determination of the number of reflections and the reflection points has not been made.

3.8 SOSUS STATIONS

Strong signals were recorded at all of the SOSUS stations along the West Coast. Hydrophone locations and other pertinent data are given in Table 3.3. The SOSUS stations utilize bottom-mounted hydrophones located far from shore and below the depth of the sound-channel axis, and are therefore capable of detecting very low-level signals. For Sword Fish, at least one channel at each station was operated at a reduced gain setting to record the higher level signals with a minimum of overload. Even so, many of these channels were overloaded by the strong initial arrival.

On many of the channels, just prior to the main arrival, there are some low-level signals which appear on the Sanborn records for 10 to 20 seconds. These are thought to be hydroacoustic signals which hit land near the hydrophone and then traveled all or most of the remaining distance as seismic waves. Following the initial strong signals which propagated directly from the burst to the receiver without reflection from land (other than possibly some bottom reflections along the path), very strong signals reflected from islands, seamounts, reefs, or other land masses continued to be received at all stations up to 2½ hours, and in some cases as long as 4 hours, after the burst. Figure 3.11 shows signals (averaged over one-minute intervals) from five of the SOSUS stations, with the sources of the major reflections indicated. The signal levels for three of these stations were obtained by using the hydrophone response curve and the settings indicated for the hydrophone amplifier and Sanborn attenuator. Unfortunately, the records from Stations UNCLE and ZEBRA did not have any indication of the Sanborn settings, and therefore, the final levels were obtained by moving the records by 5-decibel increments, corresponding to the various possible settings of the Sanborn attenuator, to the best fit with the records from the other three stations. The indicated signal level at WILLIAM, is lower than expected. (Throughout this report, unless otherwise noted, decibel levels are given re 1 dyne/cm^2.) This record may be overloaded, or the signal may have been attenuated in passing over shallow areas near Cape Mendocino.

Figure 3.12 is a combination of the five records shown individually in Figure 3.11, along with the short record available from YOKE. The levels given in this figure are those calculated for X-RAY, WILLIAM, and TARE, with the others set to the level which appears to give the best fit, as described above. Also shown in the figure is a theoretical curve of the expected wide-band signal level in deep water as a function of travel time (range), derived as will be explained in Section 4.1. Signal levels at the northern stations would be expected to be lower because of the shallow water path the signal must follow along the coast.

In normal operation, the signals received at the individual hydrophones of the SOSUS stations are combined in beam-forming equipment. The processed signals are presented in the form of a continuous Lofargram for each beam. The Lofargram is an intensity-versus-frequency and time plot, where time and frequency are the horizontal and vertical coordinates, respectively, and relative intensity is indicated by the darkness of the trace. An automatic gain control in the system limits the average darkness of the record.

All the West Coast SOSUS stations were operating normally when the Sword Fish burst occurred. The first arrival blanked out all Lofargrams for periods of

] The effects at each station are discussed below.

3.8.1 UNCLE (219 nautical miles). Lofargrams from four beams are shown in Figure 3.13. A small seismic signal precedes the main arrival by about 3 minutes, but it appears only at the lowest frequencies and would not decrease station effectiveness.

3.8.2 X-RAY (287 nautical miles). Lofargrams from all beams were examined; five of these are shown in Figure 3.14. Like UNCLE, this station received two major arrivals, the direct signal and that reflected from the Hawaiian Islands. Also like UNCLE, a small seismic signal preceded the main signal, the time difference at X-RAY being about five minutes.

3.8.3 TARE (532 nautical miles). This station also received two arrivals. Both the direct signal and the Hawaiian reflection

In Figure 3.15, the upper four records are of the standard beams, covering frequencies from 0 to 150 cps; the fifth record is a high-frequency channel, covering 130 to 280 cps. On the standard channels, the low-frequency parts of the beams were

In the fifth, the high-frequency record, the effects were of much shorter duration.

3.8.4 ZEBRA (748 nautical miles). The two major arrivals, the direct signal and that reflected from the Hawaiian Islands, caused

The upper two Lofargrams in Figure 3.16 are standard recordings, covering the 0-to 150-cps band, while the third and fourth records have expanded frequency scales, covering 40 to 65 cps and 60 to 85 cps respectively. Note that these Lofargrams all show considerable degradation, even though only the second one is from a beam fairly near the azimuth to the shot point (176°).

It is evident that the beam-forming properties of the system

do

3.8.5 WILLIAM (930 nautical miles). Figure 3.17 shows three standard beams from Station WILLIAM, and an expanded portion (30 to 55 cps) of one beam. On the three beams analyzed, the direct arrival blanked out the entire spectrum

A weak reflection from the Hawaiian Islands disturbed the system for only a minute or two. No seismic arrivals were noted prior to the main hydro-acoustic arrival. The sharp horizontal lines in Figure 3.17 are from a target being tracked by the station, and the loss of the signal, especially the low-frequency part, due to the Sword Fish signal, can be noted. Strong reflections from the region of the Tuamotu Archipelago gave considerable degradation from about 2200Z to 2240Z, especially in the 0-to 50-cps range, as may be seen in the lower Lofargram.

3.8.6 YOKE (1066 nautical miles). Only the direct arrival was of significance at this station, as may be seen from the Lofargrams of Figure 3.18. The initial arrival

(See the lower Lofargram of Figure 3.18 which covers frequencies from 30 to 55 cps.) Reflections from the south were quite strong in the lower frequencies from about 2200Z to 2248Z, but did not interfere too much with the higher frequencies.

3.8.7 Effects on the Complete SOSUS System.

after

both the main arrival and the reflection from the Hawaiian Islands. For comparison of signal level with the appearance of a Lofargram, Figure 3.19 shows a slightly smoothed representation of the wide-band record from X-RAY along with a Lofargram from the same station. It appears from this figure that if the signal level is much above

A seismic signal from Sword Fish was received at those SOSUS stations which were within 600 miles of the burst. This signal was almost entirely confined to frequencies below 20 cps and lasted no more than about two minutes. Like the signals which these stations often receive from earthquakes, this signal caused essentially no loss of station effectiveness.

3.9 MILS STATIONS

The locations of the MILS hydrophones are given in Table 3.4, together with the range and azimuth to the burst point. These hydrophones are all located near the axis of the deep sound channel, being on the bottom at Kaneohe and suspended upward to the channel axis at the other stations.

____________________________________. This station recorded the complete signal except for the initial peak which overloaded most of the Sanborn records. The station operator's notes reported that the indicated peak signal strength was

After correcting for the fact that the strongest part of the signal spectrum was in the low-frequency region where the hydrophone's response was falling off, a value of

was obtained for the wide-band signal level, which is to be compared with the expected level of

Figure 3.20(a) shows the signal after averaging over one-minute intervals. Reflections from various land masses, some of which are identified in the figure, kept the Kaneohe level well above the background for approximately one hour after the first arrival. Even though not shown on the figure, occasional strong reflections continued to be received until at least three hours after the initial arrival.

station, all channels were saturated by the initial signal. One of the records from this station is shown in Figure 3.20(b). Due to the overload conditions on all channels, the peak level cannot be determined precisely, but it is estimated to be over Signal levels at Midway were above background for at least 1¼ hours after the first signal arrival, and some reflected signals were received even later.

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all channels were overloaded by the initial signal which arrived about 2120Z. Several signal peaks during the next 5 minutes also caused overloads of short duration. Various reflected signals kept the level well above background noise for about 2 hours after the initial arrival, as shown in Figure 3.20(c). Although not shown in this figure, some reflections were received for an additional two hours. These last arrivals had been traveling for about 5½ hours, and at a speed of almost 3000 nautical miles per hour, this is over 16,000 nautical miles, or approximately three-quarters the distance around the earth.

At Wake, the peak signal strength was reported as being approximately above noise. Based on the calibration information given, the noise level was about -15 decibels, thus giving a maximum signal level of

This is approximately below the expected level for that range in open water. As the great-circle path between the Sword Fish shot point and

it is not surprising that there was considerable attenuation of the signal.

The first signals arriving at the MILS station overloaded all channels except one whose gain was set very low. After the initial arrival at about 2130Z, reflected signals were received for more than two hours, or until about 3½ hours after the burst. Some of these signals are shown and their probable reflection points given in Figure 3.20(d).

It is estimated that the actual signal level was at most

The direct path for this signal passes through the Hawaiian chain at the Gardner Pinnacles, an area of quite shallow water. Carefully made measurements of signal arrival times at the hydrophones show that the signal does indeed arrive from the azimuth of the Gardner Pinnacles, possibly passing slightly to the north. In this region the signal path would pass over an area where the water depth is considerably less than 1,000 fathoms for about 50 miles. As the expected signal level for a clear deep-water path is about

at the range of Eniwetok, the signal loss is roughly

over that expected for a free-water path. It is considered remarkable that the transmission through the island chain was as good as it was.

3.9.5 Signal levels at MILS stations. Figure 3.21 shows the signals from the four MILS stations superimposed on each other. The signal levels shown were computed using the attenuator and gain settings marked on the original records. The computations were done in the same manner as those for obtaining the signal levels at the SOSUS stations. It will be observed that in general the four records tend to follow each other rather well, with deviations where signals from strong reflectors arrive. The background noise levels of 2 decibels re 1 dyne/cm^2 are about as expected, but the levels at near -15 decibels, are believed to be too low, even in view of the expected lower shipping density in those areas of the Pacific Ocean.

3.10 FLEET SUBMARINES AT VARIOUS LOCATIONS

Reports were received from nine submarines which attempted to monitor the burst, using standard sonar equipment, while engaged in other operations. These submarines, not including the SEA FOX which was discussed earlier, are listed in Table 3.5. Although apparently two of the submarines were not monitoring when the signal should have arrived and two others reported negative results, probably because they were behind islands or other obstructions, five of the submarines received the signals. From the magnetic-tape recordings made on some of the submarines, wide-band signals had amplitudes of from   above the background noise, as recorded on the AN/BQR-2B sonar system, and lasted from 3 to 20 seconds. Passing the signals through third-octave filters improved the signal-to-noise ratios by several decibels. In some cases, a filter centered at 720 cps, for example, increased the signal-to-noise ratio by at least   It seems likely that, as in the case of the surface-ship stations, the background noise was in the low-frequency range, below 100 cps, and that it was the elimination of this component that brought about the improved signal-to-noise ratio.

The reports received from the submarines stated that Shot Sword Fish was heard as a low rumbling sound coming through the hull and that it was audible to almost all the crew.

The only submarine at closer range than 1,000 miles which gave a negative report was the QUEENFISH, and it was located in shallow water behind Santa Catalina Island from the shot.

TABLE 3.1 SWORD FISH BURST INFORMATION

Date:	11 May 1962
Time:	2002:05.91 ± 0.01Z
Latitude:	31°14.7' ± 0.5'N
Longitude:	124°12.7' ± 0.5'W
Yield:	(Radiochemical)
Burst Depth:	670 ± 30 feet
Water Depth:	13,140 ± 60 feet

TABLE 3.2 LOCATIONS OF SHIP STATIONS AT LONG RANGES FROM SWORD FISH BURST POINT

Ship	Range	Latitude	Longitude
	n.mi.		
USS TAWAKONI (ATF-114)	1673	23°38'N	154°33'W
USS ARIKARA (ATF-98)	1963	18°30'N	157°38'W
USS LIPAN (ATF-85)	2435	15°00'N	165°00'W

TABLE 3.3 SOSUS STATION HYDROPHONE LOCATIONS

This information is published

separately

and is obtainable from:

Chief of Naval Operations
ATTN: OP-321
Department of the Navy
Washington, D.C. 20350

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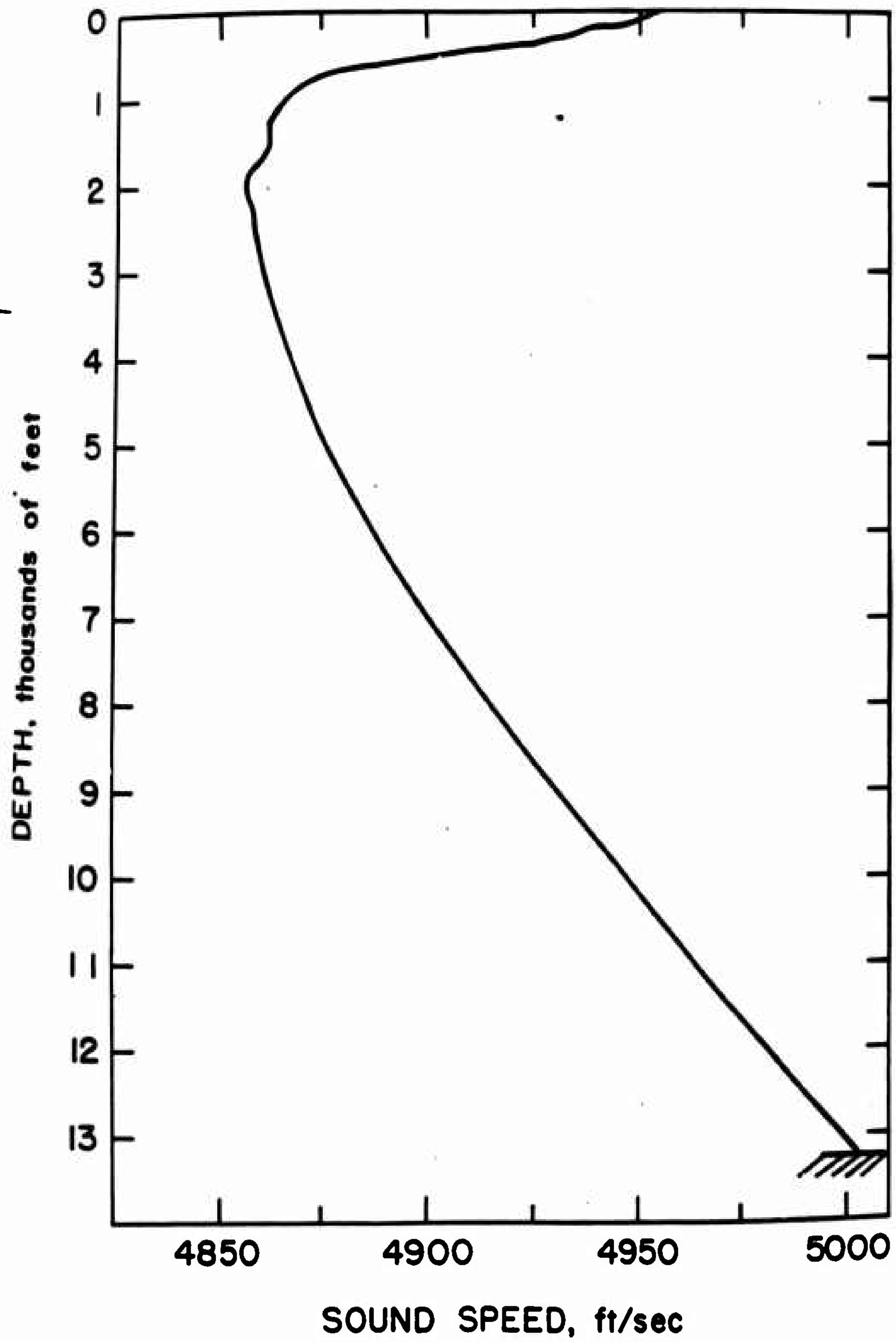

Figure 3.1 Sound-speed profile for the Sword Fish area.

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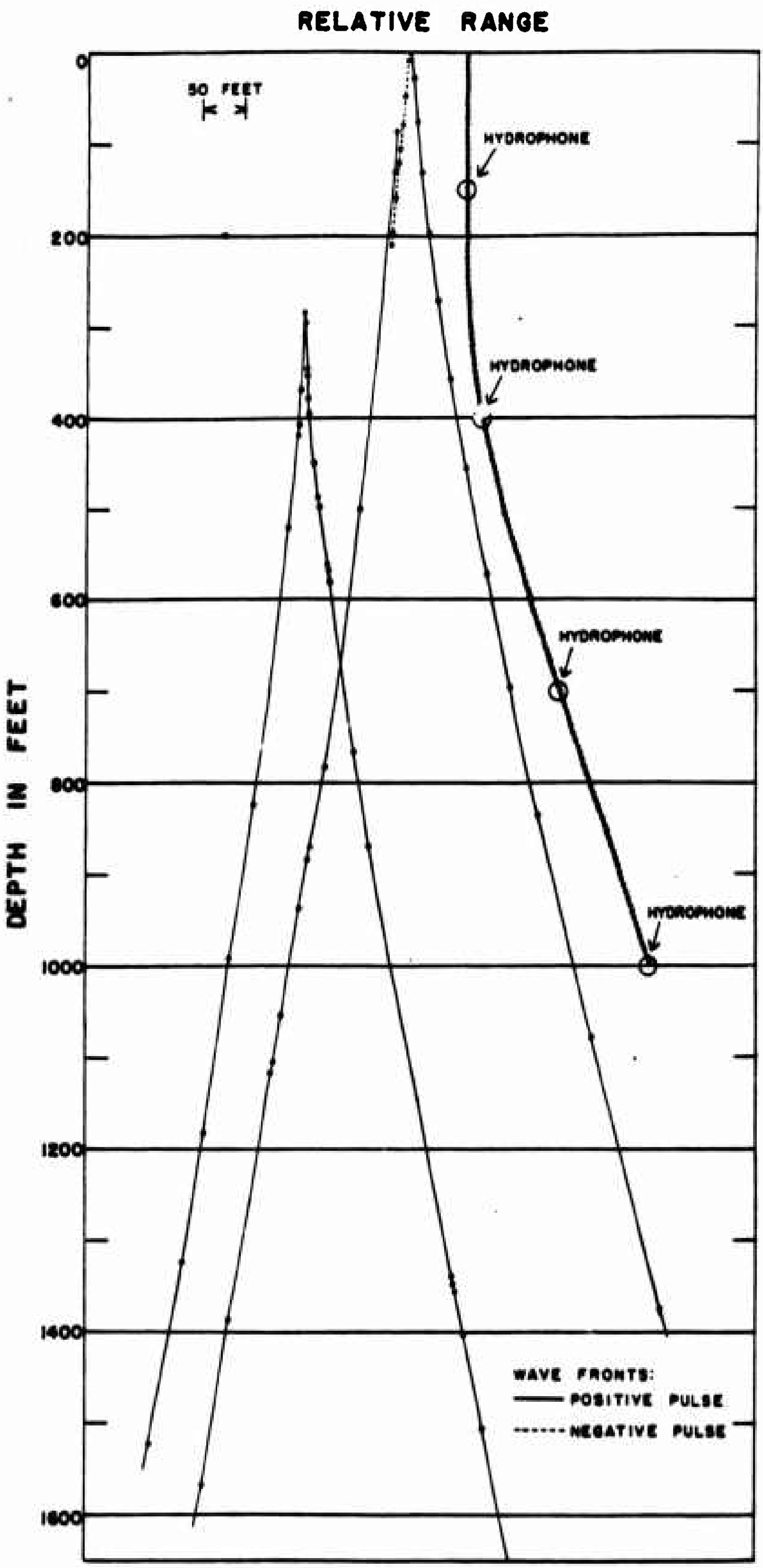

Figure 3.8 Wave fronts and estimated position of hydrophone string at 28.5 nautical miles. Dots show calculated position of rays at 0.1° intervals at a particular time.

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CHAPTER 4

DISCUSSION

4.1 THEORETICAL SIGNAL STRENGTHS

The signal level expected as a function of range has been calculated following the analysis given in Reference 20. Taking the radiochemical yield of the burst as and assuming that the TNT equivalent for underwater blast effects is of this, the effective TNT yield is . The effective source level (signal level at 1 yard) for 10 tons of TNT, based on observations and scaling, is given in Reference 20 as . This level is scaled from small-charge measurements covering the frequency band from approximately 20 to 500 cps. Scaling the pressures according to the formula

$$\frac{P_1}{P_2} = \left[\left(\frac{W_1}{W_2}\right)^{1/3}\right]^{1.13}$$

and converting to decibels, the effective source level for is found to be (This discussion ignores the fractional-decibel error resulting from the shot being off the axis of the sound channel.) Since both the MILS and SOSUS system hydrophones respond to frequencies below 20 cps, the theoretical spectrum was extended downward to 3 cps, resulting in an increase of 7 decibels in the source level, giving a total of for the frequency band from 3 to 500 cps. This is the source level which has been used in calculating the expected open-water signal level at various ranges.

The loss of signal strength due to spreading has been assumed to follow a spherical spreading law, 6 decibels per distance doubled, to a range of 10 nautical miles, and cylindrical spreading, 3 decibels per distance doubled, at greater ranges. Attenuation has been taken as given in Reference 2, $2.08 \times 10^{-6} f^{3/2}$ decibels/nautical mile, where the frequency f is in cps. By applying these two loss mechanisms to the theoretical source spectrum, spectra for different ranges were computed and are shown in Figure 4.1. These spectra were used to determine the wide-band signal levels to be expected at various ranges in open water. Since the sound travels about 3000 nautical miles per hour, the theoretical open-water signal levels at various ranges were easily converted to theoretical levels at corresponding times, and the resulting curve is shown above the experimental records in Figures 3.12 and 3.21.

4.2 RESULTS AT SHIP AND SUBMARINE STATIONS

The closest station of this project to the Sword Fish burst was the submarine SEA FOX, which made measurements at only one range, about 28.5 nautical miles. From the agreement of the measured pressures with those calculated for that range, it would appear that at the region of greatest intensity, near a depth of

670 feet and a range of 25.5 nautical miles, the pressure would

In the region shown in the ray diagram of Figure 3.2, the only area safe for the transducer is the upper left portion, where the only pressure waves are due to the bottom-reflected rays (not shown in the figure) and are not over Most of the shock pressures in the vicinity of the SEA FOX were of the order of or more due to the refraction of the sound rays (under isovelocity conditions the shock pressure would be only about

At the surface-ship stations, the average noise level was estimated to be about 35 to 40 decibels re 1 dyne/cm^2, thus making it impossible to measure reverberation levels on the wide-band records.

Of course, the reports and tape recordings from the submarines operating at long distances from the Sword Fish burst gave only qualitative information. The reports indicate that sonars at ranges of more than 100 miles may be affected for periods of a few seconds and that the sound may be heard as a dull rumbling through the hull.

It is interesting to note that even in the case of the ship stations located directly behind the island of Hawaii, the signal was still received. It seems unlikely that this signal was one which had traveled through the island of Hawaii as a seismic wave and then been reconverted to a hydroacoustic wave, for the losses in such conversion are quite large (see Reference 17). It is more likely that the signal traveled as a hydroacoustic wave for the entire distance. This, however, entails either diffraction around Hawaii or reflection from Maui and passage of the signal through the rather narrow Alenuihaha Channel between Maui and Hawaii. If the signal traveled by the diffracted path, the minimum angle through which the signal must have been bent in going around Hawaii is almost twenty degrees. This is a much larger angle than has been observed previously for the diffraction of hydroacoustic waves around obstacles. Upon first consideration, the reflection of the signal from Maui seems unlikely, because of the shallow water (less than 1,000 fathoms) along the path, but in view of the strength of the signals received at Wake and Eniwetok, which must also have traveled over shallow-water paths through the Hawaiian Island chain, it appears that this path may in fact be the one followed by the signal received at the ARIKARA. In any event, the strengths of the signals received at the ARIKARA

show that even those hydroacoustic listening stations which are not in a direct clear path to a large underwater explosion may be exposed to signals strong enough to affect their operating capabilities temporarily.

The SEA FOX was the only ship station which received a signal which had traveled most of its path as a seismic wave. This is not surprising, in view of the rather rapid damping of these relatively high-frequency seismic signals with range, the large loss associated with the double transition from hydroacoustic to seismic and back to hydroacoustic propagation, and the high noise levels at the ship stations.

4.3 RESULTS AT THE MILS AND SOSUS STATIONS

The peak signal level received at those stations which had an unobstructed path from the burst, and where the peak signal level could be determined, was about 10 decibels lower than had been expected. Peak levels at the northern SOSUS stations were still further below the theoretical open-water values because of the shallow-water path the signal encountered near Cape Mendocino. Unfortunately, signal levels could not be precisely measured at all stations due to overload conditions and lack of complete documentation of the gain and attenuator settings.

were partially shielded by the shallow-water areas of the Hawaiian Island chain through which the signals had to pass, and thus the signal levels at these two stations were understandably far below the theoretical open-water values for these ranges.

As noted, those stations for which the transmission path was unobstructed, and for which the signal strength could be measured, all showed a peak level of the order of 10 decibels below the theoretical curve shown in Figures 3.12 and 3.21. Since the theoretical curve is based on a number of assumptions and extrapolations from measurements made on signals from smaller explosions (see Section 4.1), it would not be very surprising if it were found from further tests that the curve may need to be lowered by as much as 10 decibels.

General reverberation levels, after the first ten minutes of signal at each station, were about 20 to 30 decibels above the ambient background noise, and decayed gradually until the pre-explosion background level was reached, from one to three hours later. In the case of the SOSUS stations, the levels decayed after the initial arrival, then increased upon the arrival of the reflection from the Hawaiian Islands, and then decayed again. Although isolated strong reflectors produce signals which are 20 to 30 decibels above the general reverberation level, it is the continuous, gradually decaying, general reverberation and reflections from large groups of reflectors which interfere with the effectiveness of the SOSUS stations. In a situation in which nuclear depth charges were being used, it seems very likely that the capabilities of the SOSUS system might be noticeably impaired, as the noise level might be considerably raised for rather lengthy periods of time.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. Peak pressures of were measured in the first convergence zone from Sword Fish, and it seems likely that pressures of or more were reached over limited regions. The

2. The amplitudes of the pressures measured at the first convergence zone agree well with predictions based on ray theory, but the polarities of some of the pulses do not agree with the predictions.

3.

4. A seismic signal from Sword Fish was received at some of the SOSUS stations, but it did not affect station capabilities.

5. The signal received at the ARIKARA, behind the island of Hawaii from the shot point, shows that even hydroacoustic listening stations which are moderately well hidden behind islands or other land masses may receive strong signals from a large underwater explosion.

6. At ranges greater than about 100 miles, there are no important effects on submarine sonar systems other than a noise burst of a few seconds duration.

5.2 RECOMMENDATIONS

1. Further tests, using either large conventional high-explosive charges or nuclear explosions, should be made to obtain sufficient measurements through the first-convergence-zone range to check the calculated high pressures.

2. Lorad transducer arrays should be ruggedized to permit their safe operation at convergence-zone range from large explosions.

3. Pending the determination of the largest pressures from a nuclear explosion at the range of the first-convergence zone,

4.

5. The operational implications of

6. In case of future underwater nuclear tests, shot locations and geometries should be decided upon well in advance of the test dates to permit effective project planning.

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