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F/G 8/41
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A
AFOSR-TR-84-0059

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University of Hawaii
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**Title:** Spectral Analyses of High-Frequency Pn,Sn Phases from Very Shallow Focus Earthquakes

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**Abstract:**

The Wake Island Hydrophone Array has been successfully upgraded from a 3-channel slow-speed analog cassette system to an 11-channel computer controlled digital system for continuing research on Ocean P (P0) and Ocean S (S0) phases, as well as normal, mantle-refracted P phases from underground nuclear explosions and earthquakes at great distances.
Features of the upgraded system are a large dynamic range (events from at least 4.0 to 8.0 mb can be recorded without distortion), absolute timing accuracy to 1 msec, interchannel timing accuracy to 1 msec, digital recording for ease of processing, and a 40 Hz Nyquist frequency for recording frequencies actually observed in Po/So at large distances.

Software development for compression and efficient management of the data has been successfully completed with master tapes sent to DARPA's Center for Seismic Studies for use by interested investigators.

Research papers on Po/So phases have reported on the frequency content and propagation velocities at the Wake hydrophones and across a 1600 km long deep ocean hydrophone array. At a distance of about 18° (≈2000 km) frequencies for Po/So are as high as 30 and 35 Hz, respectively; at a distance of about 30° (≈3,300 km), as high as 15 and 20 Hz, respectively. The travel time equations which successfully model all Northwestern Pacific shallow-focus Po/So first arrival data collected by the Hawaii Institute of Geophysics since 1963 at epicentral distances greater than 12° are \( T = \frac{X}{(7.96 \pm 0.05 \text{ km/sec})} - (7.14 \pm 2.38 \text{ sec}) \) and \( T = \frac{X}{(4.57 \pm 0.04 \text{ km/sec})} - (14.03 \pm 5.31 \text{ sec}) \), respectively. Values for a frequency dependent Q are found to range from 625 ± 469 at 2 Hz to 2106 ± 473 at 13 Hz for Po and from 1401 ± 296 at 5 Hz to 3953 ± 863 at 15 Hz for So. This could alternatively be described as an average attenuation of -21.5 ± 0.9 dB per 1000 km of travel path for both Po and So at all frequencies studied.

Regarding published research on normal-mantle refracted P phases, spectral comparisons for earthquakes and explosions have been completed and published. Expected differences between the spectral signatures of explosions and shallow focus earthquakes at great distances (the nuclear explosions being relatively stronger at high frequencies) are reported. The recording of a small explosion and improvement in its S/N ratio through some elementary enhancement techniques are also discussed.
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INTRODUCTION

General Objectives

General objectives of our research in deep ocean seismology can be summarized as follows:

(1) to determine the mechanism for the generation and propagation of Po/So phases; and

(2) to utilize the low noise levels at high frequencies (i.e., > 2 Hz) of the deep oceans and the relatively large amplitudes observed in P at those high frequencies from events at great distances (i.e., >> 30°) to gain new insights into: (a) differences in spectra associated with source characteristics, and (b) the physical properties of the deep mantle.

In the past two years the principal means for achieving these objectives has been through the acquisition of data from hydrophones and ocean bottom seismometers located near Wake Island.

Specific Objectives

Specific objectives of an applied nature which we believe may be of interest to AFOSR are the following:

(1) the relationship of Po/So spectra to focal depth and source parameters;

(2) spectral comparisons of normal, mantle-refracted P phases at great distances from earthquakes and explosions;

(3) estimates of the coherence of seismic phases recorded on the deep ocean floor; and

(4) comparisons of S/N ratios for phases recorded on the Wake hydrophones, ocean bottom seismometers, and ocean sub-bottom seismometers.

The specific means by which AFOSR has contributed to our efforts to achieve these objectives has been major support for the upgrading of our Wake Island hydrophone array (partial support being derived from ACDA) and for the analysis of data acquired by: (a) the upgraded station, (b) the original three channel Wake system, and (c) other ocean bottom instrumentation in the Western Pacific.

Reasons for Interest

Reasons why these applied objectives may be of interest follow.

(1) For oceanic travel paths out to distances of about 3000 km, Po/So phases have signal-to-noise ratios generally at least ten times greater than the ratios of their respective normal, mantle-refracted P and S phases; and, in many instances, no P's or S's can be found in spite of
the presence of very strong Po's and So's. Therefore, the detection and discrimination of underground nuclear explosions at distances less than about 3000 km in an ocean environment requires an understanding of Po/So. Most important could be any possible relationship of Po/So spectra to focal depth and/or source parameters.

(2) Normal, mantle-refracted P phases recorded at great distances (i.e., 60° to 90°, or approximately 6700 km to 10,000 km) have substantial amounts of energy at high frequencies (i.e., 2 Hz to 10 Hz). Such phases from earthquakes and explosions are well recorded in the low noise environment of the deep ocean. [Estimates of noise levels on the Wake bottom hydrophones in the 2 to 10 Hz range are comparable to those of the best continental sites.]

(3) A major concern in the analysis of underground explosions by seismic methods is the reliability of yield estimates. Much of the scatter in yield estimates is due to inconsistencies between the waveforms from different stations, and even between the waveforms from elements of continental arrays with apertures the size of the Wake bottom array. These differences may be attributable to variations in the response of the continental crust underlying these arrays. Signals recorded in regions where the crust is very thin (i.e., under the deep ocean basins) may have higher coherencies—thereby providing a means for improved estimates of yield. The Wake array is an ideal tool for evaluating this hypothesis.

(4) In recent years some members of the "detection and discrimination" community have demonstrated a substantial amount of interest in ocean sub-bottom instrumentation. The level of this interest may be best manifested in DARPA's commitment to develop a working sub-bottom system—the "Marine Seismic System" or MSS. Another sub-bottom instrument which has been developed (this at HIG through ONR sponsorship) is called the "Ocean Sub-Bottom Seismometer" (OSS). A reasonable presumption is that S/N ratios for ocean sub-bottom systems would be greater than for existing bottom systems (i.e., ocean bottom seismometers or ocean bottom hydrophones), resulting in a higher sensitivity (or lower detection threshold) for the sub-bottom instrument. A possible alternative to a sub-bottom instrument is an array of bottom instruments such as ocean bottom seismometers or ocean bottom hydrophones, with enough elements to make up the difference in S/N. Essential requirements to achieve an increase in S/N are incoherent noise and coherent signals in the frequency band of interest. Advantages of such an array over a sub-bottom instrument may be in cost, in ease of deployment, and in studies requiring an array. With the continued operation of the eleven element deep-ocean hydrophone array near Wake Island, these questions may be answered through further comparisons between signals recorded by the sub-bottom systems and those recorded by the Wake hydrophones.
PROGRESS

Upgrading of the Wake Island Hydrophone Array Recording System

Upgrading of the recording system for the Wake Hydrophone Array, from a 3-channel slow-speed analog cassette system to an 11-channel, 16 bit, computer-controlled digital system, was accomplished by September, 1982. Some of the advantages of this new system are: (1) a large dynamic range to record, without distortion, events ranging from at least \( \text{mb} = 4.0 \) to \( \text{mb} = 8.0 \) (i.e., 16 bits = 96 dB); (2) absolute timing generally accurate to 1 msec (for ease in processing, no time correction needs to be applied to achieve this accuracy); (3) interchannel timing accurate to within 1 msec; (4) a digital recording format such that only a minimal amount of processing is necessary to convert the data to a widely useable format; (5) the capability to record all eleven available hydrophones; (6) the recording of frequencies at least as high as those already observed at Wake in Po and So (i.e., a 40 Hz Nyquist); (7) operation of the system so simple that it can be accomplished by the personnel at Wake who are untrained in computer hardware and software; (8) required servicing (i.e., changing tapes) no more than once per day; and (9) the capability of restarting automatically after power failures (which occur frequently at Wake).

The recording of data from all eleven available hydrophones produces four full-reel computer tapes per day requiring four tape drives to maintain a maximum of once per day servicing by an operator. Several problems which have occurred with the tape drives have made it necessary to record only eight of the eleven hydrophones (thus producing only three tapes per day) during most of the recording period. All other losses of data, including those caused by power failures, amount to less than 3% of the total data collected.

Once the data on computer tape are received by HIG, an efficient compression and management of the data must be accomplished. Uncompressed, the data could amount to 1460 tapes per year, requiring a large space for storage and being inefficient to access for study, or to copy and transmit to other scientists. Software has been developed to compress this data to approximately 15% of its original volume and at the same time catalog all of the saved data for easy accessibility. Sections of data saved correspond to arrivals from events, and the raw data are also randomly sampled for future quantification of the temporal characteristics of ambient noise levels.

Compressed data tapes have been sent to the DARPA Center for Seismic Studies (CSS) for use by other scientists.

A complete description of the digital recording system at Wake, the data compression software used at HIG, and the tape format for data sent to CSS is contained in Appendix IX. A list of events for which the times of possible arrivals have been saved on the CSS compressed data tapes is contained in Appendix X.
Po/So Spectra vs. Focal Depth and Source Parameters

Although this was one of our original research objectives for AFOSR, no direct progress has been made in this area. Factors contributing to this lack of progress have been:

(a) the re-direction of efforts towards topics more readily resolved, of more immediate interest, and/or of greater apparent importance;

(b) anticipated improvements in instrumentation (i.e., the upgrading to a digital, rather than an analog system) which would greatly facilitate the data reduction required for this task; and

(c) the small number of events with very shallow focal depths (<10 km).

Indirectly, a great deal of progress may have been made towards the achievement of this objective. [It is unlikely that relationships of spectra to focal depths and source parameters could be postulated in the absence of a generally acceptable model for the generation and propagation of Po/So phases.] Evidence of continuing progress in Po/So research may be found in: (a) recent publications ("Oceanic Pn/Sn: a qualitative explanation and reinterpretation of the T-phase" by D. Walker; RIG Report 82-6; and "Spectral characteristics of high-frequency Pn. Sn phases in the Western Pacific" by D. Walker, C. McCreery, and G. Sutton; op. cit.); (b) the formation of an Ocean P Alliance with the publication of an OPA newsletter; and, (c) important advances apparent in analyses of data acquired by the ONR sponsored OBS Wake array experiment reported at the recent fall AGU meeting and now in draft form in preparation for publication. ("Po/So Phases: Propagation Velocity and Attenuation Across A 1600 km Long Deep Ocean Hydrophone Array" by D. A. Walker and C. S. McCreery).

We should note that with the upgraded system we have recorded two shallow focus events (15 km and 17 km depth) from the Marianas at distances of about 18° and one intraplate (and presumably very-shallow focus) event from approximately 12° to the west of Wake. The Po/So phases from these, and other, events will be useful in evaluating Po/So as a possible discriminant.

Spectral Comparison for Earthquakes and Explosions

Spectral comparisons between earthquakes and explosions have been completed and are the subject of a published paper ("Spectra of nuclear explosions, earthquakes, and noise from Wake Island bottom hydrophones" by C. McCreery, D. Walker, and G. Sutton, Geophys. Res. Lett., 10, 59-62, 1983.) The data examined show expected differences between the spectral signatures of explosions and shallow focus earthquakes at great distances—the nuclear explosions being relatively stronger at high-frequencies (or weaker at low-frequencies) than earthquakes. Also, a small explosion has been recorded with a significant S/N ratio on the Wake hydrophones. A unique aspect of hydrophone recordings is that the ocean surface reflection (recorded at a time after the main P corresponding to twice the water depth divided by the velocity of sound in water) can be used to increase S/N ratios.
Estimates of Coherence

Comprehensive estimates of coherence and possible improvements in yield estimates are a major topic for investigation in the coming year using data acquired from the expanded hydrophone array. Some preliminary estimates of coherence have already been made. These estimates are appended to this report.

Comparisons of S/N Ratios

In September of 1982, DARPA and ONR conducted tests (the "Downhole Experiment") in the Northwestern Pacific relating to sub-bottom seismic instrumentation. Successful deployments included OBS's and HIG's ocean sub-bottom seismometer (OSS). During the same time the expanded Wake system became operational. Preliminary comparisons of S/N ratios for the Wake system and the available downhole data have been made. They are appended to this report. Additional comparisons were (and are being) made after the OSS data was retrieved from its recording package on the ocean bottom in the summer of 1983. These comparisons will be the subject of a future report.

SUMMARY OF ACCOMPLISHMENTS

Major accomplishments supported in whole, or in part, by AFOSR since 3 March 1982 follow.

(1) Successful upgrading of the Wake Hydrophone Array recording system from a three-channel analog cassette system to a sixteen-channel digital system. Some of the advantages of this new system are: (a) the ability to simultaneously record all of the active hydrophones in the array; (b) a 96 dB dynamic range; (c) millisecond accurate absolute and cross-channel timing; and (d) a digital format which allows immediate processing of the data.

(2) Development of software to compress and manage the digital data collected at Wake. This data is compressed by saving intervals of data in which seismic phases of interest are known or suspected to be present, and by saving regular intervals of data for sampling the ambient noise levels. These compressed data are stored on magnetic tape files which are catalogued on paper and in computer files for easy reference.

(3) Preparation of a report on items 1 and 2 above ("The Continuous Digital Data Collection System for the Wake Island Hydrophones" by C. S. McCreery).

(4) Distribution of the Wake digital data through the DARPA Center for Seismic Studies (CSS). Compressed data tapes containing known or suspected seismic phases are being routinely sent to CSS for access by others who may have an interest in this data. Investigators at Rondout Associates Inc. have successfully accessed the data through CSS. A list of intervals, and the events and phases, which they represent, is contained in Appendix X. The event format of the data also is described in Appendix IX.
(5) The observation and characterization of differences in spectral signature between P from explosions and P from shallow focus earthquakes recorded on the Wake bottom hydrophones. The observations reflect differences in source spectra between explosions and shallow focus earthquakes. For similar magnitudes, explosions had more energy at frequencies above 2.0 Hz and less energy at frequencies below 1.5 Hz.

(6) The enhancement of S/N of an extremely small explosion by signal stacking to a level near that for perfectly coherent signals.

(7) The publication of a report on items "4" and "5" above ("Spectra of nuclear explosions, earthquakes, and noise from Wake Island bottom hydrophones" by C. McCreery, G. Sutton, and D. Walker; op. cit.).

(8) Continuing analyses of Po/So phases with additional spectrograms and discussions submitted for publication ("Spectral characteristics of high-frequency Pn, Sn phases in the Western Pacific" by D. Walker, C. McCreery, and G. Sutton; op. cit.).

(9) The formation of an "Ocean P Alliance" with the publication of an OPA Newsletter to stimulate interest in, and research on, Po/So phases.

(10) The evolution of a qualitative explanation for the propagation of Po/So phases consistent with many observations of these phases throughout the western, northern, and central Pacific.

(11) The discovery of a probable relationship between Po/So and T phases.

(12) Publication of a report discussing item "9" and "10" above ("Oceanic Pn/Sn: a qualitative explanation and reinterpretation of the T-phase" by D. Walker; HIC Report 82-6.)

(13) Preliminary comparisons, with available data, of the Wake hydrophones to ocean bottom seismometers and the OSS. It should be noted that these are merely preliminary studies and in some cases the comparisons made are of an indirect nature. Nonetheless, it would appear that the Wake hydrophones may be comparable to the OSS in terms of S/N ratios, considering possible improvements through array processing. Direct comparisons to MSS are not possible since that system was not successfully deployed in the Pacific. Regarding the comparisons of Wake to ocean bottom seismographs, we have observed with data from an ONR sponsored OBS experiment near Wake Island in 1981 that the Wake hydrophones have higher S/N ratios than OBS's by about 10 dB over the range 1-20 Hz.

(14) The presentation of studies on the spectra of nuclear explosions and earthquakes, as well as spectral studies of Po/So, at the 1982 DARPA/AFOSR annual review.

(15) Preparation of a report (Po/So Phases: Propagation Velocity and Attenuation Across a 1600 km Long Deep Ocean Hydrophone Array by D. Walker and C. McCreery) which quantifies the variations in velocity and spectra of Po/So phases across a long deep ocean array.
SIGNIFICANT TASKS REMAINING

(1) Consistent with our efforts to determine the mechanism for the generation and propagation of Po/So phases, a comprehensive investigation of the relationship of the T phase to Po/So will be made. This study will include spectral studies of the entire T phase coda (i.e., forerunners as well as peak signals) and comparisons of these spectra to the spectra of Po/So phases.

(2) Differences between the hydrophone/cable response (and possibly the lithosphere response) across the Wake array will be determined and removed from the data. This will be necessary to evaluate the stability of yield estimates from spectral or waveform data across the array. Such an evaluation will be made.

(3) Research on coherence across the Wake array will be completed with the coming year, and the significance of these studies in terms of possible improvements in S/N will be evaluated.

(4) S/N comparisons to the Wake hydrophones will be made with the OSS data which was retrieved from its recording package on the ocean bottom this past summer.

(5) Profiles of Po/So spectra as a function of focal depth will be made. If sufficient data is available for very shallow focus events, the possible significance of the relationships in terms of nuclear detection and/or discrimination will be evaluated.

The expanded Wake Island Hydrophone Array was successfully installed with funds provided primarily by AFOSR. However, since supplementary support of critical importance was provided by ACDA, all studies utilizing data acquired by the upgraded system should acknowledge both agencies. In the coming year ACDA funds will be used primarily on item #2 above, with the possibility that supplementary support for this task may be provided by AFOSR. On all other tasks AFOSR will be the principal supporter, with some supplementary funds provided by ACDA.
APPENDIX I
Abstract. Spectral characteristics of P phases from 4 shallow focus earthquakes and 8 underground explosions, and of 52 samples of ocean bottom background noise, are examined by using tape recordings of ocean bottom hydrophones near Wake Island from July 1979 through March 1981. Significant differences are found between spectra of large shallow focus earthquakes and explosions (5.7 < mb < 6.3) observed at 61° to 77° epicentral distance. For similar magnitudes, explosions were found to have less energy at frequencies below 1.5 Hz and more energy at frequencies above 2.0 Hz. Earthquakes were found to have a spectral slope of -28 dB/octave (relative to pressure) over the band 1 to 6 Hz. Explosions had a flat spectral slope over the band 2.2 to 6 Hz, but a different slope of -12 dB/octave over the band 1.1 to 2.2 Hz. High frequencies (>6 Hz) observed in the teleseismic P phases indicate high Q values for the deep mantle. Ambient noise levels on the ocean bottom near Wake are comparable to levels at the quietest continental sites for frequencies below 1.5 Hz. Also high levels of coherence (at least as high as 0.85) have been observed for P phases recorded on sensors with 40-km separation.

Introduction

In an earlier report (Walker, 1980), slow-speed paper recordings of hydrophones located near Wake Island were used in a study of P phases from underground nuclear explosions and earthquakes at comparable distances. That study was prompted by: (1) the work of Evernden and Keller (1979) which showed that phases observed in the 60° to 90° distance range from underground explosions were surprisingly rich in high-frequency energy (at least as high as 9 Hz); (2) the extreme sensitivity of the Wake hydrophones to high-frequency signals (Walker et al., 1978); and (3) the location of most known underground test sites in the 60° to 90° distance range from the Wake hydrophones. The major conclusion of Walker (1980) was that observable P phases were found for all Russian underground explosions with estimated yields in excess of 270 kilotons, whereas no such phases were found for earthquakes of comparable or greater magnitude at similar distances. Principal limitations of the impulsive noise and explosions investigated in this study were listed in Table 1. The events chosen because they occurred within 60° to 90° epicentral distance, were shallow focus, had large signal/noise ratios, and did not exceed the dynamic range of the recording system. Figure 1 shows the pressure spectra of some of these events, as well as composite pressure spectra for the earthquake and explosion groups. For purposes of comparison, pressure and vertical
displacement may be related using the expression:

\[ P = \omega^2 \rho V A \]

where \( P \) is pressure, \( \omega \) is angular frequency, \( \rho \) is seawater density, \( V \) is the speed of sound in seawater, and \( A \) is vertical.

**Table 1. Description of Events Used in Figure 1**

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Location</th>
<th>Distance (km)</th>
<th>( L ) : h</th>
<th>Magnitude (mb)</th>
<th>Type</th>
<th>Number of Hydrophones</th>
</tr>
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<tr>
<td>1</td>
<td>07/24/79</td>
<td>S. of Java</td>
<td>65.7</td>
<td>31</td>
<td>6.3</td>
<td>Earthquake</td>
<td>3</td>
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<tr>
<td>2</td>
<td>08/04/79</td>
<td>E. Kazakh</td>
<td>73.2</td>
<td>0</td>
<td>6.1</td>
<td>Explosion</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>08/18/79</td>
<td>E. Kazakh</td>
<td>73.2</td>
<td>0</td>
<td>6.1</td>
<td>Explosion</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>09/24/79</td>
<td>Novaya Zemlya</td>
<td>76.7</td>
<td>27</td>
<td>6.2</td>
<td>Earthquake</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>09/29/79</td>
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<td>10/18/79</td>
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<td>6.0</td>
<td>Explosion</td>
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<td>73.2</td>
<td>0</td>
<td>6.1</td>
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<tr>
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<td>11/19/80</td>
<td>Sikkim</td>
<td>70.4</td>
<td>17</td>
<td>6.0</td>
<td>Earthquake</td>
<td>2</td>
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</table>

**Figure 1. Sample spectra of \( P \) from some shallow focus earthquakes and nuclear explosions are shown in the upper portion of this figure.** Numbers refer to the events as described in Table 1. The composite spectrum of each group, an average with \( \pm 1 \) standard deviation, is shown in the lower portion of the figure. Before standard deviations were computed, individual spectrums were normalised by subtracting the difference between their mean dB value over the range 1.5-3.0 Hz and the mean dB value for all spectra over the same frequency range.
Ocean Bottom Ambient Noise

The average background noise at the ocean bottom near Wake is shown in Figure 2 (labeled A). This average, along with its standard deviation, was determined from 52 samples of noise taken over 18 months of recording. Also plotted are an assortment of published noise curves for both ocean bottom and continental sites. When compared with noise levels from continental sites, the Wake ambient noise level could be described as: (1) high for frequencies between 0.2 Hz and 1.5 Hz; (2) average for frequencies between 1.5 Hz and 3.0 Hz; and (3) low for frequencies between 3.0 Hz and 15.0 Hz.

The observed low noise levels at higher frequencies affirm the ability of the Wake hydrophones to detect seismic signals at those frequencies. In addition, high-frequency phases recorded on the deep ocean bottom, which traverse only a few kilometers of homogeneous crust, may be less distorted than similar phases recorded on continents, which often traverse more than 40 km of crust. Consequently, coherence across the array appears to be high for telesismic P.

These factors (low noise levels and a thin, homogeneous crust) have enabled the Wake array to acquire some impressive recordings of underground nuclear explosions. Shown in Figure 3 is an Eastern Kazakh explosion at 73° with a body wave magnitude of 5.9. Its signal/noise ratio is approximately 50/1. Also shown in Figure 3 is a Western Siberian explosion at 77° with a body wave magnitude of 4.6. This arrival is the weighted sum of signals from two of the hydrophones, as explained in the figure caption. Coherence between the two hydrophone signals in the band 1.5 to 5 Hz was measured at 0.85 for this arrival.

**Summary**

Significant differences are found between the spectra of P phases from explosions and from shallow focus earthquakes at 61° to 77° epicentral distance. Explosion spectra exhibit a change in spectral slope at about 2 Hz from -12 to -28 dB/octave relative to pressure. Earthquake spectra have a nearly constant slope of -28 dB/octave over the range of 1 to 6 Hz. High frequencies (>6 Hz) observed in these phases indicate a high Q in the deep mantle.

The ambient noise spectrum on the ocean bottom near Wake falls off at about -24 dB/octave over the range of 0.3 to 6 Hz. Between 3 and 15 Hz
the background noise levels are comparable to those at the quietest continental sites. Teleseismic P has been observed with a high level of coherence across a sensor separation of 40 km. The low level of ambient noise on the ocean floor at high frequencies and the high levels of coherence observed indicate that the ocean bottom may be an excellent observational regime for teleseismic P as well as other seismic phases rich in high frequencies.

Acknowledgments. This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Air Force Office of Scientific Research under Contract Nos. F 49620-79-C-0007 and F 49620-81-C-0085. Supplementary funds were provided by the U.S. Arms Control and Disarmament Agency. Installation of the recording system was partially funded by the Office of Naval Research (Code 4256G). The authors express special thanks to the Air Force and Kentron International for assistance in installing and maintaining the recording station at Wake, and to Al David for diligently changing tapes and making repairs. The authors thank Neil Fraser for critically reviewing this report and Rita Pujalet for editorial assistance. Hawaii Institute of Geophysics Contribution No. 1316.

References


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SPECTRAL CHARACTERISTICS OF HIGH-FREQUENCY Pn, Sn PHASES IN THE WESTERN PACIFIC

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Abstract. Pn and Sn phases from 25 selected earthquakes recorded since July of 1979 on ocean bottom hydrophones near Wake Island are used to complement and extend prior investigations of high-frequency Pn, Sn spectra in the Western Pacific. At a distance of about 18° (≈2000 km), frequencies for Pn and Sn are as high as 30 and 35 Hz, respectively; at a distance of about 30° (≈3300 km), as high as 15 and 20 Hz, respectively. Pn phases lose their high-frequency energy more rapidly than Sn phases do, yet Pn wavetrains are much longer than Sn wavetrains. Pn wavetrains of longer duration, more energy, and higher frequencies are found for travel paths primarily in the Northwestern Pacific Basin than for travel paths across the transition zone from the shallow Ontong-Java Plateau to the deep Northwestern Pacific Basin. Sn phases are extremely weak or absent for travel paths crossing this transition zone from the shallow Ontong-Java Plateau to the deeper Northwestern Pacific Basin, whereas Sn phases are well recorded for travel paths crossing the transition zone in the opposite direction. Although normal, mantle-refracted Pn phases are well recorded beyond about 21° (≈2300 km), available data indicate that detectable normal, mantle-refracted Pn phases may not exist at distances from about 17° to 21°.

Introduction

Recent investigations of high-frequency Pn, Sn in the Pacific [Walker, 1977; Walker et al., 1978; Sutton et al., 1978; Talandier and Bouchon, 1979; and McCreery, 1981] suggest that the real character of these phases is revealed at frequencies much higher than those traditionally associated with normal, mantle-refracted body waves at teleseismic distances (i.e., ≈1 Hz). For example, in one investigation [Walker et al., 1978], frequencies as high as 12 and 15 Hz were found for the Pn and Sn phases, respectively, of an earthquake recorded at a distance of 28.3° (3147 km).

In this report we offer a more comprehensive analysis of the spectral characteristics of Pn, Sn using additional data recorded since July of 1979 on ocean bottom hydrophones near Wake Island. Only undistorted arrivals with signal/noise ratios of at least 3/1 were used in this investigation. Epicentral distances, origin times, depths, and magnitudes are given in Table 1; and locations of epicenters are shown in Figure 1.

Northwestern Pacific Basin Travel Paths

Spectrograms for some of the Pn, Sn phases having travel paths primarily under the deep Northwestern Pacific Basin (i.e., events 1 through 18) are shown in Figure 2. All reveal high frequencies, with values in excess of 20 Hz for both Pn and Sn at a distance of 18.0° (2000 km; event 2) and values of up to 25 and 30 Hz for Pn and Sn, respectively, at a distance of 29.4° (3270 km; event 17). (More detailed spectral analyses of the phases for event 2 at 18.0° indicate values as high as 30 and 35 Hz for Pn and Sn, respectively.)

Spectrograms for events 17 and 18 show the normal, mantle-refracted P phases as well as high-frequency Pn and Sn phases. Other events for which normal, mantle-refracted P phases have been clearly recorded are 11, 12, 13, 15, and 16. The fact that all of these events are at distances in excess of 21° is not coincidental, for it is only at these distances (the precise crossover depending, in part, on focal depth) that P phases begin to arrive ahead of the high-frequency Pn phase (Figure 3). With increasingly shorter distances, high-frequency Pn arrives increasingly ahead of the expected P.

Although it might seem reasonable to assume that P does arrive at distances less than about 21°, but is masked by Pn, such an assumption should be tested. One test is to compare spectrograms where all of the P's energy, or large portions of it, might be suspected of being present within the Pn code (i.e., events 1 through 10) to the spectrograms where only Pn is known to exist (i.e., events 13 through 18; 11 and 12 could not be used due to Pn clipping). Composite spectrograms have been made for the two groups of Pn arrivals (i.e., Pn with P suspected, at distances from about 17° to 22°; and Pn with P known to be absent, at distances from about 26° to 33°), as well as for all P phases, at distances from about 22° to 33°, either clearly arriving well ahead of Pn (events 11, 12, 13, 15, 16, 17, and 18) or suspected of arriving close to, but ahead of, Pn (events 9 and 10). These composites and the individual absolute spectrograms from which they were derived are shown in Figure 4.

Individual and composite P spectra are obviously, and not unexpectedly, very different in character from individual and composite Pn
spectra, in that the P has larger signal-to-noise ratios at lower frequencies (i.e., 1-2 Hz) than either Pn grouping (Figures 4 and 5), and the composite P is richer in lows, and weaker in highs, relative to the 26° to 33° Pn composite (Figure 5a). In comparing the composite 17° to 22° Pn spectrum to the composite 26° to 33° Pn spectrum (Figure 5b), we note that the 17° to 22° Pn is similar in character to the 26° to 33° Pn for frequencies higher than 2 Hz, but has lower signal-to-noise ratios at frequencies less than 2 Hz (i.e., values fall below the "4 dB above noise" requirement for plotting). This latter observation is also apparent in the individual spectrums (Figure 4). The fact that values for the 17° to 22° Pn spectrum fall below the 4 dB requirement for frequencies less that 2 Hz, coupled with values for the 22° to 33° P spectrum above the 4 dB level at those frequencies, suggests that detectable normal, mantle refracted P phases may not exist in the Pn codas of events at distances of 17° to 22°.

Another important, though not surprising, observation to be made from the composite plots (Figure 5b) is that Pn phases at great distances appear to be weaker at higher frequencies (310 Hz) than Pn phases at shorter distances.

Sn composite plots have also been made for the same events for which Pn composites have been made. These plots are shown in Figure 6. Although normal mantle-refracted P phases have been well recorded at great distances, normal mantle-refracted S phases from earthquakes have not been recorded by the Wake hydrophones. Presumably, this is due to the small pressure signal in the water resulting from S phases at

### TABLE 1. Epicentral Distances, Origin Times, Depths, and Magnitudes of Events 1-25 in Figure 1

<table>
<thead>
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<th>Event Number</th>
<th>Distance, deg.</th>
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<th>Time</th>
<th>Depth, km</th>
<th>Magnitude, mb</th>
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<tr>
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<td>June 9, 1980</td>
<td>1923:33.3</td>
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<td>1258:55.2</td>
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<td>57</td>
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<tr>
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<td>68</td>
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<td>30</td>
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<td>Oct. 23, 1979</td>
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<td>31.1</td>
<td>Feb. 22, 1980</td>
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<td>68</td>
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Walker et al.: Spectra of High-Frequency Pn, Sn Phases

Fig. 1. Epicenter location map.

teleseismic distances. In addition, background noise levels are higher for those frequencies at which S would appear [McCreery et al., 1982].

In Figure 6a, Sn composite plots for the 17° to 22° and 26° to 33° distance ranges are compared to one another. Considering that the standard deviations of all of the composite plots presented in this paper are generally in the range of ± 3 dB, no significant differences are apparent in Figure 6a. In Figures 6b and 6c, Sn composite plots are compared to their respective Pn composite plots. Again, no statistically significant differences are indicated. In other words, Sn signal strength is generally comparable to Pn signal strength. This similarity of Pn and Sn spectrums was observed earlier for travel paths in the Western Pacific east of the Marianas [Ouchi, 1981].

Special mention should be made of the fact that the composite Sn plot in Figure 6c is 6 dB above background noise at frequencies well above 8 Hz while the composite Pn plot is not. Also it should again be noted that the individual Pn's and Sn's used to formulate the composite plots were for the same earthquakes. These considerations suggest that Sn phases do not lose their high frequencies as rapidly as Pn phases.

It has been pointed out that some high frequencies observed elsewhere might be the result of instrumental nonlinearities [Sacks, 1980] and/or nonlinear seismic interactions in the vicinity of a receiving station [Nakamura and Koyama, 1982]. As the lower frequencies are of comparable amplitude for both Pn and Sn at both distance ranges considered (Figures 6b and 6c), it is unlikely that such nonlinearities could explain the data discussed here. We also note that P, which has higher average amplitudes than
Fig. 2. Spectrograms for some earthquakes having travel paths to Wake under the Northwestern Pacific Basin. Expected times of arrivals are based on either the Jeffreys and Bullen [1958] tables for P or Pn/Sn travel time curves from Walker [1977]. These and succeeding spectrograms were made by dividing the time series into adjacent 512-point segments, Lanczos squared windowing the segments, and performing a fast Fourier transform (FFT) on each segment. In the horizontal direction, the width of each shaded block corresponds to one of the 512-point segments in the time series. In the vertical direction, each block is the average of two adjacent power spectral estimates out of the FFT. Only frequencies from 0 to 1/2 Nyquist are shown. The contour interval is 8 dB. The line at 10 Hz is due to time code cross talk. Instrument responses have not been removed.

Pn or Sn at the lower frequencies, has the most rapid falloff toward higher frequencies (Figure 5).

In all of these comparisons, another objection that could be made is that differences in source spectrums (and/or orientation of the source relative to the recording station) were not considered. Although all of the events occurred within the subducting margin of the Northwestern Pacific and the Pn, Sn phases used were generated by earthquakes having focal depths of 128 km or less, differences in source spectrums might be
significant. We believe, however, that overall trends of the individual spectrums (Figure 4) used for the composite plots are similar (as opposed to specific details that may differ) and that such similarities could justify the general conclusions drawn from that data. We also note that source effects are minimized in those comparisons of composite Pn's and Sn's from the same earthquakes (Figures 6b and 6c).

Another interesting feature of Pn, Sn phases is that the Pn wavetrain is much longer than the Sn wavetrain (Figure 2). Spectral analyses indicate that energy is lost at all frequencies in the later arriving portions of these wavetrains, and that this loss is much greater in the Sn wavetrains than in the Pn wavetrains.

Ontong-Java Plateau Travel Paths

Spectrograms for some of the more interesting Pn phases with travel paths to Wake under the shallow Ontong-Java Plateau (as well as portions of the deep Northwestern Pacific Basin) are shown in Figure 7. (Refer also to Table 1, Figure 1, and Figure 8.) The most conspicuous feature of these spectrograms is that Sn phases are extremely weak, or absent, even though Pn phases are prominent.

Figure 9 compares the composite Pn spectrum for events having Ontong-Java Plateau travel paths (events 19 through 25) to the composite Pn spectrum for events at comparable distances having Northwestern Pacific Basin travel paths (events 15 through 18). The Northwestern Pacific Basin events appear to have more Pn energy at higher frequencies than the Ontong-Java Plateau events. However, because of the approximate +3 dB standard deviation on each of these curves, this suggestion is not statistically significant. Comparing Figures 2 and 7, the duration of the Pn
wavetrains appears to be greater for the Northwestern Pacific Basin events.

In such comparisons, the important question again arises of differences in source characteristics, in this instance for New Ireland-Solomon Island earthquakes and for Japan-Kuril Islands-Kamchatka earthquakes. It is not possible, however, to attribute the absence of Sn to differences in source characteristics, as Sn phases from New Ireland and the Solomons have been well recorded at Ponape on the northern margin of the Ontong-Java Plateau [Walker, 1977]. Examples of such phases are shown in Figure 10. Of the more than forty events from the New Ireland-Solomon Islands area recorded at Ponape, amplitudes of Sn phases are at least comparable to, and frequently larger than, those of their respective Pn phases.

The absence of Sn at Wake would, therefore, appear to be a result of Sn’s inability to propagate efficiently across the transition zone from the shallower Ontong-Java Plateau to the deeper Northwestern Pacific Basin, and would suggest that much of the energy in Sn travels through portions of the lithosphere involved in the transition. On the other hand, Sn’s that have crossed this transition zone from the other direction (i.e., from earthquakes in the Marianas, Japan, the Kuriles, and Kamchatka) are well recorded at Ponape (Figure 10). Differences in the crustal structure of the Ontong-Java Plateau and the Northwestern Pacific Basin are indicated by the section profile [Hussong et al., 1979] shown in Figure 11.

Another comparison of spectrums at Wake for the two differing types of travel paths (Northwestern Pacific Basin and Ontong-Java Plateau travel paths) was made for the later arriving energy in the Pn wavetrains. For these comparisons, less energy at higher frequencies was present in those Pn’s having travel paths that include the Ontong-Java Plateau. These deficiencies and the corresponding absence of Sn for paths across the transition zone from the shallow Ontong-Java Plateau to the deep Northwestern Pacific Basin suggest that the longer, stronger Pn phases observed for travel paths to Wake, primarily across the Northwestern Pacific Basin, may be the result of more efficient conversions of Pn to Sn (or Sn to Pn).

Concluding Remarks

The phenomenon of high-frequency Pn, Sn propagation is emerging as a major unresolved property of the oceanic crust and/or mantle. Others have described high-frequency Pn, Sn propagation as "a challenge remaining to the theoretician" [Richards, 1979] and as "the challenge to both explosion and earthquake..."
Fig. 7. Some spectrograms for earthquakes having portions of their travel paths to Wake under the Ontong-Java Plateau. In comparing these spectrograms to those of Figure 2, note the absence, or weakness, of Sn. Computational procedures are the same as used in Figure 2.

Seismology for the coming decade [Hirn et al., 1973]. These descriptions are supported not only by the unusual character of the phases but also by their probable occurrence throughout the world's oceans.

As important as recent efforts are to determine the mechanism of high-frequency Pn, Sn propagation [e.g., Stephens and Isacks, 1977; Menke and Richards, 1980; Sutton and Harvey, 1981; Gettrust and Frazer, 1981], we believe that many essential characteristics of Pn, Sn phases (especially at very high frequencies) are not well known, and that accurate quantification of those characteristics through the acquisition of additional high-quality data is greatly needed. We hope that this report will further familiarize seismologists with high-frequency Pn, Sn propagation and will be viewed as a preliminary attempt to quantify, in a relative sense, some of the essential characteristics of these phases.
summary of principal observations contained in this report follows.

The apparent absence of normal, mantle-refracted P phases at distances less than about 210° (≈2300 km).

Frequencies as high as 30 and 35 Hz for Pn and Sn, respectively, at 18.0° (2000 km).

Frequencies as high as 15 and 20 Hz for Pn and Sn, respectively, at 29.4° (3270 km).

With increasing distance (i.e., from about 20° to 30°), Sn phases not losing their high frequencies as rapidly as Pn phases do.

Pn wavetrains longer than Sn wavetrains.

The extreme weakness or absence of Sn phases for travel paths across the transition zone from the Ontong-Java Plateau to the Northwestern Pacific Basin and the presence of Sn phases for travel paths in the opposite direction across this transition zone.

Longer, more energetic Pn wavetrains for travel paths primarily in the Northwestern Pacific Basin than for travel paths across the transition zone from the Ontong-Java Plateau to the Northwestern Pacific Basin.
Fig. 10. Pn and Sn phases recorded at Ponape on the northern margin of the Ontong-Java Plateau.

Fig. 11. Section profiles for the Ontong-Java Plateau and Pacific Basin as taken from Hussong et al. [1979].

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References


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APPENDIX III
OCEANIC PN/SN PHASES:
A QUALITATIVE EXPLANATION
AND REINTERPRETATION
OF THE T-PHASE

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November 1982

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Director
Hawaii Institute of Geophysics
ABSTRACT

The combined effects of: (1) differing efficiencies between Pn and Sn energy transmission across the basement-sediment interface; (2) ocean surface reflections; (3) Pn to Sn conversions; and, (4) large lateral variations in the crust and upper mantle are used to formulate a working hypothesis which appears to explain, qualitatively, many observations of high-frequency Pn/Sn phases throughout the western, northern, and central Pacific. Also, the concept of Pn/Sn phases as sources of energy at the basement-sediment interface is suggested as a possible mechanism for T-phase generation through scattering or Stoneley wave generation.
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INTRODUCTION

High-frequency Pn/Sn phases were first observed nearly fifty years ago for travel paths in the Atlantic from the West Indies to the northern east coast of the United States (Leet et al., 1951, reported that these observations were made as early as 1935). The history of research on these phases since that time has been given by several authors, with some of the more recent being Molnar and Oliver (1969) and Walker (1977a).

My interest in the phenomenon began in 1963 with the recording of long-range, high-frequency Pn/Sn phases on hydrophones of what was then known as the Pacific Missile Range facility. My efforts at trying to understand these unusual phases (Sn wavetrains greater than Pn wavetrains with frequencies as high as 15 Hz at distances in excess of 3000 km; Walker et al., 1978) has continued since those initial observations. A reasonable, concise summary of my accomplishments prior to this report might be that no answers were found—only more questions. Such methodology can only be rationally tolerated for a length of time much shorter than my tenure on the case. So, for the past few years, it has been hoped that a working hypothesis could be found that would permit many, if not all, of the diverse observational pieces to be fitted together in at least a qualitative sense. Such a hypothesis could then serve as an appropriate starting point for comprehensive and detailed quantitative analyses leading to a generally acceptable model for the generation and propagation of long-range, high-frequency Pn/Sn phases. A working hypothesis has now emerged and is the subject of this report.

SN SIGNAL STRENGTH

One of the most interesting aspects of long-range, high-frequency Pn/Sn propagation in the northwestern Pacific is the strength of the Sn phase (Walker et al., in press). Relative to Pn, Sn often appears stronger at great distances—even at high frequencies (Fig. 1). A possible explanation for these observations begins with considerations of: (1) the efficiencies of Pn/Sn energy transmission across the basement-unconsolidated sediment interface; (2) possible conversions of Pn and Sn at the basement-sediment interface; and, (3) ocean-surface reflections. Observations of conversions upward and across the basement-sediment interface, as well as ocean-surface reflections for short travel paths
off the coast of California are reported in Auld et al. (1969), where data indicate that the percentage of P (perhaps actually Pn) energy converted to S is greater than the percentage of S (perhaps actually Sn) energy converted to P. Examples of ocean-surface reflections are also given in Shimamura et al. (1975) and McCreery et al. (in press).

The very recording of "Pn/Sn" phases on ocean-bottom sediments is evidence that Pn and Sn energy does propagate, by some means, into the sediments. Energy losses above the basement-sediment interface will occur, i.e. not all of the energy passing into the sediments will be returned to the interface by way of reflections from the ocean surface. These losses could be much greater than those produced within that portion of the waveguide below the basement-sediment interface. Furthermore, if the percentage of Sn energy lost after propagation up through the basement-sediment interface, as S or converted P or both, is less than the percentage of Pn energy similarly lost up through this interface, then Sn would retain a greater percentage of its initial energy within that portion of the waveguide below the basement-sediment interface.

Under these assumptions Sn signal strength could increase with distance relative to Pn signal strength—even at high frequencies.

PN WAVETRAINS

In spite of Sn's greater signal strength, its wavetrain is considerably shorter than Pn's (Figs. 1 and 2). This seemingly peculiar observation can be explained by considering other types of conversions.

Any phases, originally Pn or Sn, that pass upward through the basement-sediment interface may eventually be reflected by the ocean surface (or the sediment-water interface) and returned to the basement-sediment interface to continue, somewhat weakened, in the waveguide as Pn or Sn or both. Throughout the travel path to the station, original Pn's returning to the interface and continuing in part as Sn's, as well as original Sn's returning to the interface and continuing in part as Pn's, would arrive between the main Pn and Sn phases. The net effect of such conversions would be Pn wavetrains greater in their duration than Sn wavetrains.
Fig. 1. Spectrograms for some earthquakes having travel paths to Wake under the Northwestern Pacific Basin. Expected times of arrivals are based on either the Jeffreys-Bullen tables (1958) for P or Pn/Sn travel time curves from Walker (1977a). The contour interval is 8 db. The line at 10 Hz is due to time code cross talk.
6 September 1982; 01:47:02; 29.3N, 140.3E; 6.6 M; 167 km; South of Honshu; Distance = 25.2°

Fig. 2. Digitally rectified and compressed plot of P, Pn, Sn, and T phases for an earthquake south of Japan recorded by the Wake Island hydrophones.
OCEAN-SURFACE REFLECTIONS

Other potentially significant contributors to the Pn, as well as Sn, wavetrains are multiple ocean-surface reflections of all Pn/Sn variations observed on the ocean bottom that are capable of becoming compressional water waves at the sediment-water interface. Such reflections have already been proposed in synthetic Pn model studies (Gettrust and Frazier, 1981). An example of an ocean-surface reflection is shown in Figure 3.

PN/SN PHASES AT GREAT DISTANCES

Another puzzling aspect of Pn/Sn propagation is the frequent absence or weakness of Sn, yet presence of Pn, at great distances (often more than 4000 km) throughout the North Pacific (Walker, 1977a and b) and Central Pacific (Talandier and Bouchon, 1979), in spite of stronger Sn's than Pn's for relatively homogeneous travel paths across the deep Northwestern Pacific Basin.

A possible explanation is that paths other than those across the relatively homogeneous deep Northwestern Pacific Basin are likely to encounter relatively large lateral changes in the crust and upper mantle. These changes would have to be of such a nature so as to reduce Sn signal strength without seriously affecting the Pn phase. Large lateral changes could be produced by plateaus, rises, ridge systems, island and seamount chains, fracture zones, transform faults, fossil arcs and trenches, and rafted continental fragments.

Specific examples of Sn's severely attenuated by large lateral variations are found in recordings of earthquakes from the Solomon Islands area on the Wake hydrophones. Although these events are at distances comparable to events from Japan and the Kurils which have strong Pn/Sn phases (Fig. 1), only their Pn's are well recorded (Fig. 4). Furthermore, this effect cannot be attributed to differences in source mechanisms because Sn's from the area are well recorded at Ponape (examples of such recordings are shown in Fig. 5; refer to Fig. 6 for the location of Ponape). A reasonable explanation would appear to be the large structural changes associated with the transition from the shallow Ontong Java Plateau to the deeper Northwestern Pacific Basin (Figs. 6 and 7). An additional factor may be the extension of the Caroline Archipelago through this region.
WAKE HYDROPHONE RECORDING OF UNDERGROUND EXPLOSION

7 JULY 1979  03:46:58.3  50.06N.79.11E E. KAZAKH

$M_B = 5.8$  $YIELD = 100 \text{ kt}$  $DISTANCE = 73.1^\circ$

S/N RATIO = 50/1  ESTIMATED MAGNIFICATION @ 2 Hz = $10^6$

1 SEC.

SURFACE REFLECTION (NEARLY EXACT INVERSE OF FIRST FIVE PULSES)

Fig. 3. An example of ocean-surface reflections.
Fig. 4. Some spectrograms for earthquakes having portions of their travel paths to Wake under the Ontong-Java Plateau. Computational procedures are the same as used in Fig. 1.
Fig. 5. Examples of Pn and Sn phases recorded at Ponape on the northern margin of the Ontong-Java Plateau. Of more than forty events from the New Ireland-Solomon Islands area, amplitudes of Sn phases are at least comparable to, and frequently larger than, those of their respective Pn phases.
Fig. 6. Bathymetry map of the Northwestern Pacific area.
Fig. 7. Section profiles for the Ontong-Java Plateau and Pacific Basin (from Hussong et al. 1979).
T-PHASE MECHANISMS

Tolstoy and Ewing (1950) recognized the importance of a sloping bottom in the production of T-phases, and Milne (1959) provided a specific mechanism involving multiple reflections between the surface of the ocean and its downward sloping bottom. Although such a mechanism could be significant for T-phases originating in areas with the appropriate downward sloping bottom, many strong T-phases have been observed from regions where the ocean floor is level or at a greater depth than adjacent areas in the direction of the receiver (Johnson et al., 1968; Duennebier, 1968). Included among these regions are the deep ocean floor off the coast of California and Oregon, the deep ocean floor south of the subducting margins of the Northern Pacific and east of the Western Pacific, and the East Pacific Rise.

Because of these observations, a mechanism other than downslope propagation is required. Some suggestions included ocean surface scattering (Johnson et al., 1968), scattering from the sea floor by fault scarps near the source (Johnson and Norris, 1970), and coupling of Stoneley waves into the SOFAR channel (Biot, 1952; Duennebier, 1968). All of these proposed mechanisms, including downslope propagation, presume that the energy of the T-phase comes ultimately from P and, perhaps, S phases travelling upwards through the crust to the ocean bottom near the T-phase source location; however, with such a presumption, none of the proposed mechanisms is capable of explaining T-phase forerunners. In describing these forerunners, Johnson (1963) stated:

"The time of earliest perceptible arrival is probably primarily a function of magnitude as the signal emerges slowly from the ocean background noise... Early, low-level arrivals, undetected in most T-phase recordings, must be normal-mode ground waves or, at least, must have followed a ground path for a significant portion of their travel."

He also states that in one instance (a 7.0-Ms earthquake from the Kurils) the forerunners were so early that "the transformation from P or S waves to sound channel waves would have to occur at a distance of about 1; 21° from the source toward the receiver." In describing a P, S, and T phase (Fig. 8; actually the P and S phases are Pn and Sn phases) from a large (6.2 mb) earthquake in the Marianas recorded on hydrophones near Enewetok Atoll at a distance of about 18°, Duennebier (1968) notes that "the T phase does not have a definite onset and that energy was continuously received at the hydrophone after the arrival of the P wave."
Both authors suggest that the apparent coupling into the SOFAR channel was due to normal, mantle P or S waves or both refracted by the Emperor Seamount Chain (Johnson, 1963) and by several groups of seamounts in the Northwestern Pacific Basin (Duennebier, 1968). In terms of frequency content and strength of signal, however, the energy from the long-range, high-frequency, guided Pn and Sn phases seems more likely to be coupled into the SOFAR channel than the mantle-refracted P and S phases which are extremely weak at high frequencies. At teleseismic distances frequencies of P and S generally do not exceed 3 or 4 Hz, while Pn, Sn, and T frequencies may be as high as 20 Hz (Figs. 8 and 9).

For large earthquakes sufficient energy could be contained in the Pn/Sn phases for coupling into the SOFAR channel throughout the travel path to the receiver. This coupling could occur by any of the mechanisms proposed for the generation of the T-phase (i.e., scattering or Stoneley waves or both), with seamount enhancement remaining as an important consideration. In effect the Pn/Sn phases would serve as potential sources of energy at the sediment-basement (or water-sediment) interface. As Pn/Sn energy declines with increasing distance, the amount of energy coupled into the SOFAR channel would also decline, thus producing a T-phase signal which would slowly emerge from the ocean background noise. A recently recorded example of such an emergent T-phase is shown in Figure 2. Energy arriving at 02:08 corresponds to a Pn path of 9.6° at 8.0 km/sec and a T-phase path of only 15.6° at 1.5 km/sec.

Finally, an additional explanation for Sn appearing to have relatively more energy than Pn with increasing distance could be that Pn energy is coupled more efficiently into the SOFAR channel than Sn energy is.

SUMMARY

Vast regions of the world's oceans are characterized by thinly layered, homogeneous crustal and uppermost mantle structure. This report suggests that comprehensive observations of high-frequency phases, often referred to as Pn/Sn, throughout the Western, Northern, and Central Pacific may be explained by a waveguide which extends upward from the uppermost mantle through the crust and, to some extent, into the sedimentary layers and the entire water column. Pn energy is more efficiently propagated upward into the sedimentary column than
Fig. 8. Sonogram of Pn, Sn, and T phases (after Duennebier 1968). Note that the T-phase does not have a definite onset. Instead, energy appears to be continuously received at the hydrophone after the arrival of the P wave.
Fig. 9. Spectrums for the P, Pn, Sn, and T phases shown in Figure 2.
Sn energy, and, because of this, Pn is more rapidly attenuated than Sn. As distance increases, Pn's losses above the basement-sediment interface produce a relative strengthening of the Sn phase, such that Sn eventually has more energy than Pn.

The observed data also suggests that the long Pn/Sn wave-trains may, in part, be the result of multiple ocean-surface reflections near the receiver.

Pn to Sn and Sn to Pn conversions are suggested to explain Pn wavetrains consistently longer than the wavetrains of Sn. These conversions could occur when Pn or Sn energy passes through the basement-sediment interface and is returned to that interface by way of reflections from the ocean surface to continue in the waveguide, at least in part, as Sn or Pn phases. Such conversions might be produced at any of the interfaces encountered by Pn or Sn, or their converted phases.

In conjunction with the scattering mechanisms and Stoneley wave propagation already proposed to explain T-phase observations, Pn/Sn phases as sources of energy at the sediment-basement interface could explain: (1) the generation of T-phases in regions not having the downward sloping ocean bottom required by the classical downslope mechanism of Milne (1959) and (2) T-phase forerunners extending well ahead of the peak arrivals--occasionally beginning perhaps as early as the Pn and/or Sn phases. Also, another explanation for Sn having more energy than Pn is provided if Pn energy is more efficiently transmitted than Sn energy into the SOFAR channel.

Finally, the observed data suggest that large lateral variations in the crust and upper mantle may produce significant reductions in Sn signal strength without seriously affecting the Pn phase.

CONCLUSIONS

Although many puzzling observations of long-range oceanic Pn/Sn phases may be resolved by the suggestions presented in this report, many of these suggestions can, and should, be tested quantitatively. These analyses could include the re-examination of existing data, new experiments, and theoretical modeling efforts leading to the generation of complete synthetic seismograms. Furthermore, one should not forget that the mechanisms for the generation and propagation of the main Pn and Sn phases are still not generally agreed
upon, nor have proposed models been matched in a comprehensive manner with observations. Such tasks are of utmost importance if the phenomenon is to finally achieve the status it deserves as a major geophysical feature and tool for mapping the crust and uppermost mantle of the world's oceans—this after nearly fifty years of being little more than an obscure curiosity.

Regarding the T-phase, it seems appropriate that the earth's most efficient acoustical waveguides, the SOFAR channel and the Pn/Sn waveguide, finally should be related; and in the hypothesis formulated in this report, the SOFAR channel is energized by leakage from the Pn/Sn waveguide. The recognition of this relationship could be an important, and perhaps critical, factor in arriving at a comprehensive understanding of these oceanic phases.

"In the bulletin of the Harvard Seismograph Station, under date of September 15, 1935 attention was directed to the unusual character of certain records from the vicinity of 17°N, 62°W. One of the novel features was a short-period phase about 23 minutes after P. It has become known as T, for third, with P and S constituting the first and second groups of short-period waves of similar general appearance...Actually, many features of P and S are abnormal on this and later records from certain areas at this distance range, and work on that part of the problem is in progress, but the investigation of T has been undertaken first." (Leet et al., 1951)

ACKNOWLEDGMENTS

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Special appreciation goes to Charles McCreery, George Sutton, and Loren Kroenke for constructive comments and discussions. Editorial assistance was provided by Barbara Jones.
SUPPLEMENTARY NOTE

It may be appropriate at this time to suggest that a new name be given to the high-frequency compressional and shear phases often observed at great distances in the world's oceans. The difficulty with the nomenclature used to date is that: (1) an, as yet, unsubstantiated relationship to the well known and much studied longer-period Pn/Sn phases of continents is inferred; and (2) the environmental feature most strongly linked to the observations is not cited. Thus, a more logical term would be "Ocean P" or "Ocean S" with the abbreviations being "Po/So." With this change, those unfamiliar with the phenomenon would not be as likely to make the false assumption that the phases are similar to continental Pn and Sn. Such assumptions in the past have been a major stumbling block in stimulating interest and support for "Po/So" research.
REFERENCES


**Title:** Oceanic Pn/Sn Phases: A Qualitative Explanation and Reinterpretation of the T-Phase

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**Key Words:**
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**Abstract:**
The combined effects of:
1. Differing efficiencies between Pn and Sn energy transmission across the basement-sediment interface;
2. Ocean surface reflections;
3. Pn to Sn conversions; and,
4. Large lateral variations in the crust and upper mantle are used to formulate a working hypothesis which appears to explain, qualitatively, many observations of high frequency Pn/Sn phases throughout the western, northern, and central Pacific. Also, the concept of Pn/Sn phases as sources of energy at the basement-sediment interface is suggested as a possible mechanism for X-phase generation through scattering or Stoneley wave generation.
CORRECTIONS AND ADDITIONS

Page 12, line 5
after "... (Duennebier, 1968)."
add "Northrop (1972) also suggests a transformation from P to T at a distance of about 17° to explain the earliest perceptible T phase arrivals on Oahu hydrophones from the 28 March 1964 Alaskan earthquake."

Page 12, line 27 (last sentence of 2nd paragraph)
"... path of 9.6° at 8.0 km/sec and a T-phase path of only 15.6°..."
should read "... path of 10.1° at 8.0 km/sec and a T-phase path of only 15.1°..."

Page 12, line 32 (last sentence of 3rd paragraph)
after "... than Sn energy is."
add "Conversions of Pn or Sn to T near the receiver could also strengthen and extend the Pn and Sn wavetrains."

Page 15, line 28 (last sentence of 4th paragraph)
after "... the SOFAR channel."
add "Conversions of Pn or Sn to T near the receiver could strengthen and extend the Pn and Sn wavetrains."


A Preliminary Informal Comparison of Signal/Noise Capabilities Between The Wake Bottom Hydrophone Array, The Ocean Sub-Bottom Seismometer, and Ocean Bottom Seismometers

by

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Abstract. A comparison has been made between noise levels and signal/noise (S/N) ratios of the Wake Bottom Hydrophone Array (WBHA), the Ocean Sub-Bottom Seismometer (OSS), and Ocean Bottom Seismometers (OBS's) using data which has recently become available. The general purpose of this comparison is to evaluate WBHA as a possible alternative or complement to deep sea drillhole seismometers such as the Marine Seismic System (MSS) now being developed and tested for possible deployment in the Northwestern Pacific Basin. Absolute noise measurements show roughly comparable levels between WBHA and OSS, although the OSS data was scant. S/N ratios were found to be approximately 17 dB greater on the OSS than on a nearby OBS over the band 2-20 Hz, and 10 dB greater on WBHA than on a nearby OBS over the band 1-20 Hz. Improvements in WBHA S/N ratios of at least 3 dB and up to 11 dB, by stacking the water surface reflections and all 6 hydrophone signals, may be gained depending upon the level of coherence between signals. An evaluation of coherence levels has revealed apparent differences between the individual hydrophone/cable responses. Appropriate correction factors for these differences will have to be determined and then applied to the data before coherence levels are accurately known. The limited amount of data available for the noise and S/N ratio comparisons, and the indirect route by which the comparisons were made are arguments for attaching a certain amount of skepticism to the results. Additional OSS data which will become available after May 1983 should provide for a more direct and statistically stronger comparison.
Introduction. Considerable effort has been expended in recent years to develop a deep-sea borehole seismometer such as DARPA's Marine Seismic System (MSS) and the Hawaii Institute of Geophysics (HIG) Ocean Sub-Bottom Seismometer (OSS), which can be deployed down drillholes in the ocean bottom. Impetus for this effort has come from a desire to make high quality seismic observations on the vast portions of the earth covered by oceans. Although seismic observations in the oceans are capable of being made more or less routinely using Ocean Bottom Seismometers (OBS's) sitting on top of the sediments, it has often been presumed that an instrument located below the sediment-basalt interface would have significantly greater signal/noise (S/N) ratios, at least for upwardly arriving signals. This is because such an instrument should receive more energy from seismic signals arriving from below, and less energy from noise propagating downward through the water column and sediments.

Since July of 1979, HIG has monitored on a nearly continuous basis, an array of hydrophones located near Wake Island in the Northwestern Pacific Ocean. This array consists of six hydrophones on the ocean bottom at 5.5 km water depth in a 40 km, 2-dimensional grouping, and 3 pairs of hydrophones at 1 km water depth (SOFAR channel) spread over 300 km. Recordings from only two or three of the hydrophones were made prior to September 1982; subsequently recordings from eight of the hydrophones have been made. The array was installed with the hydrophones hardwired to Wake Island more than 20 years ago for the purpose of recording transient, non-tectonic signals at frequencies above 10 Hz. Recordings made by HIG indicate that the hydrophones are also excellent seismic sensors in at least the band 0.5-20 Hz. The capability to evaluate the full potential of this array as a seismic tool has only been possible since the September
1982 upgrading. One aspect of this evaluation is to compare the noise levels and the S/N ratios between the Wake Bottom Hydrophone Array (WBHA), a sub-bottom seismometer (the OSS), and an OBS. Although data for a direct comparison does not yet exist, a somewhat indirect comparison has been made using data collected recently. That comparison is the subject of this report.

**Absolute Background Noise Levels.** In September 1982, during Leg 88 of the R/V Glomar Challenger, the OSS was successfully deployed off of the Kuril Islands, 378 m below the ocean floor and 20 m below the sediment-basalt interface. For a period of about 2.5 days, data was recorded from the OSS directly on the ship. Then a 2 month continuous recording package was dropped over the side for pickup sometime in May 1983. Briefly overlapping this 2.5 day period was the nearby deployment of several HIG OBS's. Noise levels measured at about the same time by the OSS vertical seismometer and a representative OBS vertical seismometer are shown in Figure 1. Although the general shape of the curves is similar, the difference in absolute levels is striking. Some of this difference is due to the impedance difference between the basalt and the top of the sediment. Smaller signals, as well as lower noise levels, would be associated with the higher impedance of the basalt. If normalized to the sediment impedance by a $\sqrt{\rho c}$ correction, where $\rho$ is density and $c$ is compressional velocity, the OSS noise curve moves up by about 9 dB to the position of the dashed curve. The remaining differences between these two noise curves may reflect the attenuation of downwardly propagating noise energy. Some of this noise is certainly generated by the research vessels which were operating overhead.
Figure 1. Background noise level measurements from WBHA (one hydrophone, 52 samples over 18 months), from an OBS and the OSS deployed in the NW Pacific Basin (vertical component-1 simultaneous sample) and the MSS in the Atlantic (vertical component-1 sample). The dashed curve is the OSS curve adjusted by 9 dB to normalize it to sediment impedance.
Also shown in Figure 1 is the average background noise for one of the Wake bottom hydrophones, determined from 52-2 minute random noise samples taken over a period of 18 months. Pressure has been converted to vertical particle velocity by the expression \( \ddot{x} = \frac{P}{\rho c} \), where \( \ddot{x} \) is vertical particle velocity, \( P \) is the pressure, \( \rho \) is seawater density, and \( c \) is the speed of sound in seawater. Although the hydrophone noise is certainly not generated entirely by vertically arriving pressure waves (thus vertical particle velocity), this conversion is useful to determine an equivalent noise level for comparison.

For reference purposes, the noise curve for MSS in the Atlantic has also been plotted. It is not known if an impedance correction need be applied to this curve and so none has been.

The OBS and OSS noise curves may not be representative of average noise levels because they are only 1 sample and because of the ship generated noise. The relationship between these two curves however, is probably significant, and illustrates the decrease in noise level which can be achieved by a downhole instrument. The average noise level of the Wake bottom hydrophone is similar to that of the normalized OSS curve. These two curves are also comparable to the MSS curve for frequencies between about 4 and 10 Hz.

**Signal/Noise.** Although absolute noise levels are important for evaluating the usefulness of a seismic sensor, a more important parameter is S/N. Ideally, a comparison should be made of an earthquake or explosion signal recorded simultaneously on the Wake hydrophones, an OBS, and a downhole instrument, all located in close proximity. Unfortunately, these data do
Figure 2. S/N measured on WBHA and on the OSS relative to S/N measured on nearby OBS's as described in the text. The lower OSS curve is based on shot S/N data, while the upper OSS curve is based strictly on noise data. The dashed curve is the WBHA curve raised by 11 dB to show the potential S/N by signal stacking.
not exist. With a few assumptions however, an indirect comparison can be made using data which do exist.

Within the 2.5 day period of OSS data previously mentioned is the record of a 126 pound shot at 80 km distance. It occurred, however, after the last of the nearby OBS's had been recovered. Fortunately, during the OBS deployment there was an 1800 pound shot also at 80 km distance from one of the OBS's. After making some assumptions and corrections, a comparison between ground arrivals on these records may yield information about the improvement in S/N between the OBS and OSS. The first correction is one for shot size, equal to the ratio of the shot weights to the power 0.66, or 15 dB. The spectral shape of the two shot records is very similar so a common shape was assumed. The second correction is for temporal changes in background noise which occurred during the time between the shots. These effects were compensated for by assuming the same OBS/OSS noise ratios found for the simultaneous data discussed in the previous section. The resulting ratio of \( \frac{\text{OSS S/N}}{\text{OBS S/N}} \) is plotted in Figure 2.

Also shown is a curve which represents the possible gain in S/N of the OSS relative to the OBS based strictly on the simultaneous noise data. A correction for the impedance difference between the sediment and basalt has been applied. No assumptions were made about possible losses in upcoming signal levels between the OSS and OBS, and the effect of these would be to raise this curve by some amount. However, the near agreement in absolute level between this curve and the one based on the shot data may imply that these losses are not significant for the frequencies observed. (The parallel nature of the two curves is not significant but is due to having used the simultaneous noise data to correct for temporal differences in the
shot data.) On the average, these data support an improvement in S/N over the range 2-20 Hz of about 17 db.

A more direct comparison can be made between WBHA and an OBS. In August of 1981, HIG deployed an OBS array along a 1500 km line in the NW Pacific, and one of these OBS's was located within the bounds of WBHA. A strong Po (i.e., "Ocean P"; formerly called high-frequency Pn) signal from a large earthquake in the Kuril Islands was recorded simultaneously by this OBS and by a recording system connected to 3 of the hydrophones of WBHA. A comparison between the OBS vertical geophone and WBHA could not be made because that sensor was not working properly on the OBS. Consequently, the OBS hydrophone signal has been used. To correct for any difference in S/N between the OBS vertical and OBS hydrophone, a factor equal to the actual measured difference in S/N between the vertical geophone and hydrophone for this same signal recorded on another OBS at a closer epicentral distance was added to the S/N of the hydrophone. This factor averaged 1 dB over the range 1-20 Hz. Plotted in Figure 2 is the ratio between the average S/N of the 3 Wake hydrophones and the S/N measured on the OBS hydrophone with the previously described correction added. The somewhat wild behavior of this curve, such as the jump from -1 dB at 6 Hz to 20 dB at 8 Hz, is not entirely understood. It may be related to resonances in the OBS package which contribute to the OBS noise level, or it may be due to other factors which could not be identified by the analysis of only this one signal. For most frequencies, however, the WBHA data show an improvement in S/N, and this improvement averages roughly 10 dB over the range 1-20 Hz.

A natural question to ask is: "Why should there be any difference at all in S/N between the OBS hydrophone and the nearby WBHA hydrophones, since they are both lying at the top of the sediment column?" One explanation
might be that the OBS used for comparison was particularly noisy due to noise sources in the water very close by or due to electrical noise in the amplification and recording system. Evidence which generally contradicts this hypothesis is that the noise levels measured on the other OBS's in the array were comparable. An alternate explanation may be related to the 20 year age of the array, and the possibility that the bottom hydrophones are now buried under a layer of sediment. Burial of the hydrophones would isolate them from noise generated by bottom water currents flowing around them, and also possibly from sediment surface phenomena such as Stonely waves. Although these explanations are not supported by direct evidence at this time, it would certainly be worthwhile to learn that shallow burial of a hydrophone under the sea floor sediment would greatly improve its S/N capabilities.

Coherence Across WBHA. An important aspect of current research at HIG is the investigation of coherence of teleseismic body waves across the 40 km aperture of WBHA. The impact of near receiver structure on these signals may be small due to the thin and relatively undisturbed nature of the oceanic lithosphere underlying WBHA. High coherency would have important implications for: (a) the planning of any future ocean seismic arrays; (b) studies of first arrivals requiring a great deal of timing precision; (c) studies requiring precise determination of seismic amplitudes (such as yield determination), and especially (d) studies of small signals where enhancement of S/N is desired (such as detection). Highly coherent signals may be added (with appropriate propagation delays) to yield an increase in S/N equal to the square root of the number of sensors (for uncorrelated noise). At WBHA the theoretical increase in S/N would be equal to about 11
9 dB (3 dB of which comes from the first water surface reflection which is well established as having nearly perfect coherence with the initial arrival). Data from 3 WBHA hydrophones, collected prior to September 1982 on slow-speed cassettes, indicated high levels of coherence for a sampling of teleseismic P arrivals. Unfortunately, these data were not especially suited for this type of analysis because of timing inaccuracies and the suspect fidelity of the recording medium. Since September 1982, however, continuous data from 5 of the 6 bottom hydrophones have been collected digitally, essentially solving the timing and fidelity problem, and providing a format for a much speedier and more accurate analysis of the data. Software for the necessary quantitative analysis is still under development. However, "eyeball" checks for coherency have been made for a few of the digitally recorded teleseismic P phases with large S/N. The results are encouraging although not entirely conclusive.

Figure 3 illustrates the kind of broadband coherency which seems to be characteristic of the different P arrivals examined. Some features are "in phase" across the array while others are not. Certain pairs appear more coherent than other pairs. This relationship does not seem to be a function of epicentral distance or azimuth. Certainly a large improvement in S/N would not be expected from the stacking of these signals as they are.

Possible reasons for the observed difference in signals may be classified into the following categories: (a) major differences in the coda exist for very small changes in takeoff angle (for Figure 3, much less than 1°); (b) variations in lithospheric structure directly beneath the array have a significant impact on the signals; and (c) the hydrophone/cable responses differ significantly across the array. If the
Figure 3. Unfiltered first arrivals of P across the Wake bottom hydrophones from an earthquake south of Honshu, Japan (6 Sept. 1981, h=167 km, m=6.6). Traces have been offset by travel time differences.
explanation is (a) then little, if any, improvement in coherence can be expected by massaging the data. If the explanation is (b) then significant improvements in coherence are possible, provided the lithospheric response does not vary greatly with small changes in azimuth or angle of incidence of incoming P arrivals. If the explanation is (c) then an even more significant improvement in coherence is possible. The technique which will be used to investigate (b) and (c) is basically a calculation of amplitude and phase differences between hydrophones for a given signal as a function of frequency. If (c) is true, then these differences should be consistent regardless of what kind of signal is being recorded - P, Po, So, T, or noise. If (b) is true, then the differences should be consistent for P and possibly Po and/or So. If both (b) and (c) are true, the effects should be separable. These effects may then be removed by a deconvolution of the observed signals with the empirically determined impulse responses of the lithosphere and hydrophone/cable. Determination of these responses to a level of statistical significance will require the recording and analysis of a variety of signals at assorted azimuths and epicentral distances which have strong S/N. Evidence exists to suggest that at least (c) is true.

Figure 4 shows amplitude differences observed across WBHA for a 10 minute section of record which includes a P, Po, and So signal. The upper curve is the absolute value of the maximum difference in amplitude observed between the six hydrophone signals as a function of frequency. Energy below about 0.5 Hz is from microseisms while between 0.5 Hz and 20 Hz it is mostly an average of the P, Po, and So. The lower curve shows amplitude differences between two particular hydrophones. Although it may seem unusual to have combined energy from all of these different types of signals, the individual signals, P, Po, So, and noise, exhibit the same
Figure 4. Plot of differences between spectra across the Wake bottom hydrophone array for a 10 minute section of record containing P, Po and So signal and noise. The upper curve shows the maximum value of variation in level between all of the hydrophones. The lower curve shows the difference in level between two of the hydrophones.
relationships although with a somewhat greater scatter. This strongly suggests that there are at least differences in the hydrophone/cable responses which are removable. These differences might easily produce the incoherencies seen in Figure 3. Further and more careful analysis of other events will necessary to precisely determine the differences in amplitude and especially phase. The reward may be stronger coherency and thus an increase in S/N.

Conclusions. The data presented in this report indicate that WBHA, the OSS, and, by inference, the MSS, are seismic tools of comparable quality. Noise levels measured were similar for all three although the data were somewhat limited. S/N ratios measured for OSS were greater than that for individual WBHA hydrophones by an average of about 7 dB. Gains in S/N levels, through stacking of the WBHA signals, will reduce, if not eliminate or reverse, that difference. Precise estimation of the coherence across WBHA will not be made until recently discovered differences in the hydrophone/cable responses have been more accurately determined so that their effects may be removed from the signals.

Many of the comparisons in this report were made via rather indirect routes due to the limited amount of data. Additional data should become available sometime this summer after the OSS recording package has been picked up and the data returned, reduced, and distributed. More data from the August 1981 Wake OBS Experiment will be in a reduced form soon. Also, data from OBS’s deployed during the OSS experiment by Oregon State University should be available later this year. All of these future data should be examined and added or compared to those data presented here to
further understand these results.

Acknowledgements. This preliminary and informal report was sponsored by the Air Force Office of Scientific Research, with supplementary funds provided by the U.S. Arms Control and Disarmament Agency. Major upgrading of the Wake system in September of 1982, just prior to the Downhole Experiment, was made possible through the timely support of those agencies.
Po/So Phases: Propagation Velocity and Attenuation Across a 1600 Km Long Deep Ocean Hydrophone Array

by

Daniel A. Walker and Charles S. McCreery

both at

Hawaii Institute of Geophysics
2525 Correa Road
Honolulu, Hawaii 96822
ABSTRACT. Po/So phases from numerous earthquakes along the margin of the Northwestern Pacific Basin were successfully recorded by a linear, 1500 km ocean bottom hydrophone (OBH) array deployed for two months near Wake Island. Data from ten shallow-focus (<100 km) events at 18° (2000 km) to 33° (3700 km) epicentral distance were used to compute propagation velocities for Po and So. The resulting travel-time equations T=X/(7.96 ± 0.05 km/sec) - (7.14 ± 2.38 sec) and T=X/(4.57 ± 0.04 km/sec) - (14.03 ± 5.31 sec) for Po and So, respectively, successfully model all Northwestern Pacific Basin shallow-focus Po/So first arrival data collected by the Hawaii Institute of Geophysics since 1963 at epicentral distances greater than 12°. Also, arrivals from an event in the Kuril Islands (mb = 6.6, h = 45 km), which propagated down the axis of the array, were used to estimate the attenuation of Po and So between 25° (2800 km) and 33° (3700 km) epicentral distance. After a correction for cylindrical spreading, values for a frequency dependent Q are found to range from 625 ± 469 at 2 Hz to 2106 ± 473 at 13 Hz for Po and from 1401 ± 296 at 5 Hz to 3953 ± 863 at 15 Hz for So. These same data may be alternatively described as exhibiting an average attenuation of -21.5 ± 0.9 dB per 1000 km of travel path, which applies to both Po and So at all frequencies studied.
Introduction

Late in the summer of 1981, the Hawaii Institute of Geophysics (HIG) successfully deployed a 1500 km long linear array of twelve ocean bottom hydrophones (OBH's) near Wake Island (Fig. 1). Half of the instruments (indicated by open circles) started recording on 12 August and ended on 23 September. The remaining half started on 3 September and ended on 15 October. The total recording time was about 65 days, with all twelve instruments in operation from 3 September through 23 September. Of the twelve OBH's deployed, ten were successfully recovered, and nine of these had quality data throughout their operational period. Recorded concurrently were three bottom hydrophones of the Wake Hydrophone Array (WHA), a 40 km array of sensors located near, and cabled directly to, Wake Island. WHA data were used in the study of first arrivals, and were considered to be part of the OBH array data. All of the OBH and WHA instruments were in ocean depths between 5265 m and 5657 m. Of more than 130 events identified from seismic phases in the recordings, 108 were located by the National Earthquake Information Service (NEIS; Table 1 and Fig. 1). The primary purpose of the experiment was to acquire data of critical importance in understanding a phenomenon known as high-frequency Pn/Sn, long-range Pn/Sn, or Pn.f./Sh.f.; but referred to here as Po/So or Ocean P/Ocean S after Walker (1982).

Po/So phases were first observed in the North Atlantic and have been found throughout the North, Western, and Central Pacific. First arriving Po/So energy travels with a fairly constant apparent velocity (epicentral distance/travel time) of about 8.0 and 4.6 km/sec, respectively, while peak amplitude arrivals have apparent velocities of about 7.6 and 4.5 km/sec, respectively, which are comparable to basal crustal rates. At distances of about 180° (~2000 km), observed frequencies of Po/So are as high as 30 and 35 Hz, respectively; and at distances of about 300° (~3300 km), as high as 15 and 20 Hz, respectively. The signal/noise ratios for Po/So phases are generally at least ten times greater than the ratios of their respective normal, mantle-refracted P and S phases; and in many instances no P's or S's can be found in spite of the presence of very strong Po's and So's. Aside from the SOFAR channel of the world's oceans, the Po/So waveguide appears to be the earth's most efficient acoustical waveguide. Also, it seems probable that the phenomenon is a dominant feature of all of the world's oceans and marginal seas.

Recent efforts have been made, using synthetics, to determine the mechanism of Po/So propagation (e.g., Stephens and Isack, 1977; Menke and Richards, 1980; Sutton and Harvey, 1981; and Gettrust and Frazer, 1981), although many essential characteristics of these phases are still poorly known. Data collected before this experiment, composed almost entirely of events recorded at single stations and over an unevenly distributed range of epicentral distances, made difficult the precise determination of the travel-time curve between 0° and 40°, as well as the attenuation of these phases as a function of frequency and distance. These parameters need to be accurately determined so that a unique model can eventually be found.

To exemplify this point consider Fig. 2: a plot of apparent velocity versus epicentral distance for Po and So having Northwestern Pacific travel paths and source focal depths of 100 km or less which is based on data collected and published (Walker, 1981) by HIG before this experiment. Two
Table 1. Events Recorded by the OBH Array  
(Data from NEIS Monthly Lists)

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<th>Location</th>
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Legend: h - event depth (km); m - body-wave magnitude; M - surface-wave magnitude; n - number of instruments in array which recorded body-wave phases P, Po, or So from this event; Po - number of Po arrivals from this event used in first-arrival study; So - number of So arrivals from this event used in first-arrival study.
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Legend: h - event depth (km); m - body-wave magnitude; M - surface-wave magnitude; n - number of instruments in array which recorded body-wave phases P, Po, or So from this event; Po - number of Po arrivals from this event used in first-arrival study; So - number of So arrivals from this event used in first-arrival study.
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Legend: h - event depth (km); m - body-wave magnitude; M - surface-wave magnitude; n - number of instruments in array which recorded body-wave phases P, Po, or So from this event; Po - number of Po arrivals from this event used in first-arrival study; So - number of So arrivals from this event used in first-arrival study.
Figure 1. Map showing OBS locations and epicenters of earthquakes recorded by the array (see Table 1). Instruments operating from 12 August through 23 September are indicated by open circles. Those operating from 3 September through 15 October are indicated by closed circles. Three instruments which did not work properly are flagged. Event numbers (from Table 1) are indicated for epicenters of events specifically used in this study.
Figure 2. Apparent velocity ($V_T$) versus epicentral distance ($X$) for Po and So with Northwestern Pacific travel paths and focal depths of 100 km or less. Note the discontinuities at 12° and 30°. Solid and dashed lines represent the mean apparent velocity plus and minus one standard deviation over the three distance ranges. This plot is based on data compiled before the OBH experiment.
significant features of this plot are the lower apparent velocity values at distances less than 12° and greater than 30° in comparison to values within the 12° to 30° range. The large amount of scatter coupled with insufficient sampling near 12° and 30°, however, make the exact nature of these velocity transitions unknown. For the purpose of modeling, it is important to know if these transitions are smooth or abrupt, and might therefore represent a gradual increase in velocity with depth or a discontinuity in velocity at some depth.

Similar difficulties arise when attempting to use older data to estimate the attenuation of Po/So energy as a function of travel-time (or distance). The high frequencies and large signal/noise ratios observed would indicate that their attenuation must be significantly smaller than that of normal, mantle-refracted P or S phases at similar distances. However, these observations might also be due in part to a frequency-dependent Q combined with low noise levels at the higher frequencies (> 4 Hz) where Po/So are most prominent. Unfortunately, the mix of data (i.e., different earthquakes recorded at only single stations) make it hard to separate attenuation from other factors which influence the observed amplitudes such as magnitude, focal depth, epicentral distance, source orientation, and possibly azimuth.

To help clarify these uncertainties, an experiment was designed to record Po/So across a linear, 1500 km array consisting of 12 OBH's. The data provided by such an experiment would permit determination of Po and So phase velocities independent of the source parameters, thus hopefully eliminating the major source of scatter in velocity estimates. Data from the experiment would also facilitate a nearly direct measure of attenuation as a function of frequency and travel-time (only a spreading term would have to be assumed in order to determine the apparent Q). In addition, any other changes in the Po/So coda would for the first time be observed at several distances along approximately the same azimuth.

The array was aimed towards northern Japan and the southern-most islands of the Kuril chain (Fig. 1), and was positioned to provide data across the 30° transition zone previously described. This target was chosen because of its long history of moderate-to-large earthquakes and several successful recordings of Po/So phases from this region on the hydrophone installation at Wake Island. Of the events recorded by the OBH array in the Marianas through Kuril portion of the circum-Pacific arc, the largest (a 6.6 mb; event 40 in Table 1) occurred in the target area while all of the instruments were recording.

Po/So Propagation and Apparent Velocity

To confirm the assumption that much of the scatter in Fig. 2 can be attributed to errors in the epicenters and/or origin times of these single station data points (i.e., no more than one station recorded any given earthquake), a similar plot has been constructed for some of the OBH data (Fig. 3). Although this data as a whole exhibits scatter of about the same magnitude as that shown in Fig. 2, there is significantly less scatter within each subset of data representing individual events at several OBH's. Thus, the larger source of scatter may be attributed to apparent velocity differences between events; and a strong possibility is that these
Figure 3. Apparent velocity \( v(V/T) \) versus epicentral distance \( X \) for some of the Po and So data collected during the OBR experiment. Data points numbered 1 through 6 represent each set of first arrivals recorded across the OBR array from events 40, 48, 49, 52, 61, and 85, respectively. Note that the scatter of each subset is less than the scatter of the combined data.
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differences are a result of errors in NEIS origin times and hypocenter locations. The remaining scatter within each subset may be the result of: (1) uncertainty in the time of onset, (2) OBE location errors, (3) OBH clock correction errors, and/or (4) local differences in crustal and sediment structure between OBH's. Unfortunately, the magnitude of this remaining scatter is enough to cause an unacceptable level of uncertainty in the propagation velocity of Po or So for any given event. An uncertainty of 1 sec in travel-time over 500 km of the array at a phase velocity of 8.0 km/sec will produce an uncertainty of 0.13 km/sec in the determination of that phase velocity, as well as an uncertainty of 5.0 sec in the travel-time intercept for data taken at an average epicentral distance of 2500 km. To reduce this uncertainty, a method was sought to determine propagation velocity and travel-time intercept by combining the first arrival data of all the events in a way which would have the following important properties: (1) propagation velocity would be determined from the differences in travel time between OBE's for a given event and would be independent of the NEIS origin time published for the event; (2) events recorded on more instruments would be weighted more heavily; (3) events recorded over a larger range of epicentral distance would also be weighted more heavily; and (4) the travel-time - epicentral distance relationships within the data set of each individual event would be maintained. The following method satisfactorily meets those requirements.

Using only those events with focal depths of 100 km or less, having Northwestern Pacific Basin travel paths, and recorded with distinct onsets at two or more stations (see Table 1), the raw epicentral distance and travel time data were computed using NEIS epicenters. For each subset of data associated with a single event, the mean epicentral distance and travel time was computed and subtracted from the raw data for that event to yield zero-meaned data for each event, as well as for the data as a whole. From these combined data the slope of the travel-time line could be computed, but the intercept would be lost (it would be exactly zero). Consequently, the mean for all of the raw epicentral distance and travel-time data was computed and added to each point of the zero-meaned data set to restore the intercept. The travel-time lines computed from these data, and shown in Fig. 4, represent the best available estimates of Po/So velocities at distances between about 2400 and 3400 km. These values (i.e., inverse slopes) are 7.96 ± 0.05 km/sec and 4.57 ± 0.04 km/sec for Po and So, respectively. The large negative intercepts found, -7.14 ± 2.38 sec and -14.03 ± 5.31 sec for Po and So respectively, imply that the first arriving energy propagates at a higher velocity than indicated by the inverse slopes over some portion of the travel path nearer to the source than where the observations were made.

In Fig. 5, we have superimposed Po/So data from the Wake OBE experiment (solid triangles) on Fig. 2. It is obvious that these data do not support the discontinuity in apparent velocity at 30° which was a feature of the older data; but they appear, instead, to describe a smooth transition across this boundary. A re-examination of the older data, especially those data points near the offset, was made to determine if the cause of this discrepancy could be found. Consequently, the original computer cards used to calculate epicentral distances for data collected in 1963 and 1964 were found to contain systematic errors in the coordinates of some recording sites. The formerly classified status of these sites and
Figure 4. Modified travel-time plots for $P_0$ and $S_0$ as described in the text.
Figure 5. Po and So data from the ORH experiment (solid triangles) superimposed on Fig. 2a and Fig. 2b, respectively. Note that these data do not support a discontinuity in apparent velocity at 30°.
the circuitous route by which these coordinates had been previously obtained may be an explanation for these errors. The erroneous data have been plotted as open circles and the corrected data as solid circles (along with the rest of the older data) in Fig. 6. Also plotted in Fig. 6 (as open triangles) are some additional hydrophone data from the analog cassette recording system at Wake, collected since 1978. It is clear from this comprehensive data set that an apparent velocity discontinuity at 30° is no longer supported by the data. Instead, a gradual decrease of apparent velocity with distance is observed between about 12° and 38° for both Po and So. This characteristic of apparent velocity is entirely compatible with the inverse slope propagation velocity and intercept values computed from the OBH data and shown in Fig. 4.

To illustrate this compatibility, the travel-time equations have been converted into relationships between apparent velocity and epicentral distance as follows:

\[
T = X/V + I
\]

Travel-time equation where \( T \) is travel-time, \( X \) is epicentral distance, \( V \) is propagation velocity, and \( I \) is the travel-time intercept.

\[
A = X/T = X/(X/V + I)
\]

Apparent velocity equation where \( A \) is the apparent velocity.

\[
S_A^2 = \frac{(X/V+I)^2V^4S_v^2 + X^4S_v^2 + X^2V^4(S_I^2+S_0^2)}{V^4(X/V+I)^4}
\]

Mean-squared error in apparent velocity, \( S_A^2 \), resulting from errors in: the propagation velocity, \( S_v \); the travel-time intercept, \( S_I \); the epicentral distance, \( S_X \), due to epicenter errors; and the observed travel-time, \( S_0 \), due to errors in origin-time.

Plotted in Fig. 7 are \( A \), and \( A \pm S_A \) versus epicentral distance, \( X \). Values for \( V \), \( S_v \), \( I \), and \( S_I \) are those given in Fig. 4; \( S_X \) is 10 km; and \( S_0 \) is 1 sec. Values used for \( S_X \) and \( S_0 \) are reasonable for epicenter/origin-time data taken from the NEIS listings, and these lists have been used for all of the data in the figure. The figure shows that approximately one standard deviation of the data (ie. 68 percent for normally distributed
Figure 6. This figure is the same as Fig. 5 except that: (1) erroneous data from 1963 and 1964 (open circles) have been replotted as closed circles; and (2) additional hydrophone data from Wake, collected since 1978, are plotted as open triangles.
Figure 7. This figure contains the data from Fig. 6, representing all of the Po and So first arrival data from shallow-focus events with Northwestern Pacific Basin travel paths collected by HIG since 1963. Superimposed on these data are curves representing the Po and So travel-time equations (Fig. 4), with plus and minus one standard deviation, determined strictly from the OBH data. Note that most of the data beyond 12° epicentral distance falls within the bounds described by these curves.
data) falls within the bounds of $A S_A$. It is concluded, therefore, that the first arrival times of $P_o$ and $S_o$ phases from shallow-focus (i.e., focal depths less than 100 km) earthquakes occurring along the margin of the Northwestern Pacific Basin with travel paths greater than $12^\circ$ epicentral distance across the Northwestern Pacific Basin, may be successfully modeled by the travel-time equations given in Fig. 4.

An important question which remains to be answered is: By what methods of generation and propagation are the first arrivals on both sides of the $12^\circ$ apparent velocity discontinuity produced? In spite of those modeling efforts mentioned previously, which have successfully reproduced certain aspects of $P_o/S_o$ travel-time and coda, no model as yet exists which addresses this question or reproduces the observations which led to this question. A hypothesis proposed here, which seems to contain some credibility, is that energy observed at less than $12^\circ$ has propagated from near the source to near the receiver entirely within the waveguide (i.e., up the descending lithosphere and across the plate), while first-arriving energy observed at greater than $12^\circ$ has propagated along a higher velocity, or deeper, $P$ or $S$ type path over distances less than $12^\circ$ before coupling into the waveguide at a distance greater than $12^\circ$. (The term "waveguide" refers here to the structure within which $P_o/S_o$ energy propagates at the constant velocity value given in Fig. 4.) Evidence which supports this hypothesis is: (1) the apparent velocity data observed for $P_o$ and $S_o$ at distances less than $12^\circ$ could reasonably be fit by a zero-intercept linear travel-time equation with a propagation velocity equal to the propagation velocity found for the data beyond $12^\circ$ (This would imply that the propagation velocity and thus the structure of the waveguide are continuous across $12^\circ$ — an intuitively pleasing result.); and (2) the apparent velocities for shallow-focus $P$ and $S$ at $12^\circ$ (from Jeffreys and Bullen, 1958) are near those required for $P$ and $S$ to couple into the $P_o/S_o$ waveguide and produce the observed arrival times beyond $12^\circ$. Although a propagation mechanism of this type might fit the data quite well, a velocity model of the oceanic crust and upper mantle which produces this phenomena has not been found. It is probable that such a velocity model would contain lateral heterogeneities associated with the downgoing slab in order to propagate energy between $0^\circ$ and $12^\circ$ with an average velocity greater than the waveguide velocity, and still couple this energy into the waveguide. This requirement is not easy to satisfy (and may be impossible to satisfy) with a radially symmetric velocity model.

One test of this proposed hypothesis could be made by examining $P_o/S_o$ arrivals from earthquakes with depths greater than 100 km. $P_o/S_o$ energy has been observed and recorded by HIG for many earthquakes with focal depths greater than 100 km and up to 600 km. Energy which has propagated along a $P$ or $S$ type path before coupling into the waveguide should contain a depth dependence in travel-time, coda, and/or frequency content. The precise nature of such a dependence would serve to either confirm or deny the hypothesis, or to generate a new one.
As stated earlier, one of the more remarkable features of Po/So is their high-frequency content; therefore, a major goal of Po/So research in recent years has been to quantify those properties within the earth in terms of Q which permit the efficient transmission of these frequencies over great distances. When a frequency-independent model for Q was fit to some older Po/So data with frequencies between about 2 and 10 Hz, the resulting Q values were greater than 5000 in most cases (Walker et al., 1978 and Sutton et al., 1978). These values are much higher than those generally found for upper mantle travel paths using P and S data at frequencies below 2 or 3 Hz. A frequency-dependent Q, however, might satisfy both sets of observations. Sutton et al. (1983) found two methods for extracting a relationship between Q and frequency from single-station Po/So data. They found that Q was approximately proportional to frequency over the range 2-9 Hz and that the Q of So was higher than the Q of Po for any given frequency.

Data collected during the OBH experiment provided, for the first time, the opportunity to observe Po/So energy propagating across a large array of instruments. Although Po/So phases from numerous events were recorded, the magnitude 6.6, Kuril Is. event noted earlier (event 40, Table 1) was especially well suited for a study of attenuation. Its large magnitude and its location in the area targeted by the array produced Po/So phases which travelled down the axis of the 1500 km deployment line with sufficient energy to be observed with high signal/noise ratios on many of the instruments.

Fig. 8 shows the spectra of the Po and So coda from the Kuril event at five epicentral distances corresponding to the five OBH's that were used. These spectra have been computed from a series of contiguous 512 point FFT's taken on the time series data which was digitized at 80 samples per sec. The spectral energy has been summed over an apparent velocity window extending from 8.2-7.0 km/sec and from 4.7-4.0 km/sec for Po and So, respectively, and has also been summed over a 1 Hz band at any given frequency. Instrument response has not been removed; however, the response of each individual OBH is presumed to be identical so that intercomparison of the spectra is valid. Only signal levels which were at least 4 dB above background noise levels, at any given frequency, have been plotted. A correction for cylindrical spreading has also been applied to these spectra so that the losses observed in the figure represent attenuation due to anelasticity, scattering, tunneling, and/or any mechanism other than cylindrical spreading. Note that in general the energy level falls off at a constant rate with distance, regardless of frequency. Also note that the attenuation of So with distance is about the same as that for Po.

A general expression for the observed amplitude of seismic signals of this type is:

$$A(f) = A_0(f) r^{-b -\pi f p q(f)[r-1]}$$

where $A(f)$ is the observed signal amplitude at a given frequency,

$A_0(f)$ is the source amplitude at a given frequency,

$f$ is the given frequency,
Figure 8. Spectra of Po and So from a large event in the Kuril Is. observed at five epicentral distances corresponding to five OBR's. Spectral energy has been summed over the apparent velocity ranges 8.0 - 7.2 km/sec and 4.7 - 4.0 km/sec for Po and So, respectively. The effect of cylindrical spreading, amounting to only 1.3 dB between 24.6° and 33.3°, has been removed from the data. Only signal levels at least 4 dB above ambient noise levels have been plotted. Dashed portions of the spectra are for continuity only and do not represent actual data at those frequencies.
\( r \) is the epicentral distance,
\( b \) is the spreading parameter (0.5 for cylindrical spreading; 1.0 for spherical spreading),
\( p \) is slowness (i.e., travel-time/epicentral distance),
and \( q(f) = Q(f)^{-1} \) is the apparent anelastic attenuation coefficient.

Conversion of the observed amplitude into decibels gives:

\[
20 \log_{10} A(f) = 20 \log_{10} A_0(f) - 20 \log_{10} (r) - 20 w f p q(f) [r-1] \log_{10}(e)
\]

Rearranging terms and differentiating with respect to \( r \) gives:

\[
\frac{d(20 \log_{10} A(f) + 20 \log_{10} (r))}{dr} = -20 w f p q(f) \log_{10}(e)
\]

Therefore:

\[
\frac{-20 w f p \log_{10}(e)}{Q(f) = q(f)^{-1} = \frac{d(20 \log_{10}(A(f)r^b))}{dr}}
\]

Each curve plotted in Fig. 8 represents \( 20 \log_{10}[A(f)r^{0.5}] \) at a given \( r \) for a range of frequencies. At any given frequency, we know \( 20 \log_{10}[A(f)r^{0.5}] \)
at several \( r \)'s and can thus determine \( \frac{d(20 \log_{10}[A(f)r^{0.5}])}{dr} \) by simple linear regression. All other quantities in the equation for \( Q(f) \) are known. \( Q(f) \) has thus been found for data sampled in one Hertz bands, and these values are plotted in Fig. 9. Although cylindrical spreading (\( b = 0.5 \)) has been assumed, the spreading term plays only a minor role in these calculations. A choice of spherical spreading would raise the values of \( Q(f) \) by no more than about 10 percent. Only frequencies where data exist at all five distances have been used. The standard deviations shown include contributions from the error in the determination of \( \frac{d(20 \log_{10}[A(f)r^{0.5}])}{dr} \), the error in slowness which is due to sampling the data over a range of slownesses, and the error in frequency due to sampling over a 1 Hz band. This method gives values for \( Q(f) \) roughly proportional to frequency, and gives higher values of \( Q(f) \) for \( S0 \) relative to those for \( P0 \) at any given frequency. These results are consistent with those found by Sutton et al. (1983) mentioned earlier, although the absolute levels for \( Q(f) \) are lower at any given frequency in this study. The relationship between the \( Q(f) \) values of \( P0 \) and \( S0 \), \( Q_P(f) = 1.4 Q_S(f) \), is markedly different from the relationship \( t_P = 4 t_S \), which implies \( Q_S(f) = 0.44 Q_P(f) \), found by others (see for example Cornier, 1982).

The nature of the \( Q(f) \) values suggests that a simpler mathematical model might be used to describe the attenuation of \( P0/S0 \). This is because...
Figure 9. Values for $Q(f)$ plus and minus one standard deviation as explained in the text are plotted versus frequency for both Po and So.
values for \( fpq(f) \) are approximately the same for any given frequency and slowness (ie., \( Po \) or \( So \)). Thus, the form of this model is:

\[
A(f) = A_0(f) e^{-b(r-1)}
\]

where "\( a \)" is the coefficient of attenuation. In this expression, the change in signal amplitude over some propagation distance is not a function of frequency or slowness as in the previous expression containing "\( q \)". By a method similar to that described earlier it can be shown that:

\[
-20 \log_{10}(e) = \frac{d\{20 \log_{10}[A(f)r^{0.5}]\}}{dr}
\]

equals the decibel change in amplitude after a cylindrical spreading correction, per unit propagation distance. The right-hand side of the above equation may be evaluated by linear regression, using the set of values for \( 20 \log_{10}[A(f)r^{0.5}] \), which can be computed from the observed values for \( A \) at a given \( r \) (and for a given frequency band), versus \( r \). Values for \(-20 \log_{10}(e)\) have been computed and tabulated in Table 2. The same data set used to determine the \( O(f) \) values discussed previously has been used to compute values in the table. With the exception of two lower values for \( Po \) at 2 Hz and 3 Hz and the slightly higher average values for \( Po \) relative to \( So \), it could be said that the data generally support the assumption that "\( a \)" is nearly a constant value for both \( Po \) and \( So \) at any of the frequencies examined.

All of the data can be combined by a zero-meaning method, similar to that described for combining the first arrival data, to yield a single value for \(-20 \log_{10}(e)\). These modified data are shown in Fig. 10, and the regression line fit to them has a slope of \(-21.5 \pm 0.9 \) dB per 1000 km of travel path. Also shown are regression lines fit to the subsets of \( Po \) and \( So \) data which have slopes of \(-19.7 \pm 1.4 \) and \(-23.6 \pm 1.1 \) dB per 1000 km, respectively. Differences between the \( Po \) and \( So \) values reflect those differences observed in Table 2. Note that all of the data lie at five distances corresponding to the five OBH's. Also note that the data points at each distance do not cluster about the central regression line, but tend to cluster about some value away from the line. It is possible that these shifts, amounting to a few dB at most, are due to differences between individual OBH responses. These differences may exist because of complexities in processing the slow-speed cassette tapes, and uncertainties in the absolute calibration of the individual hydrophones. Computation of new regression lines, under the assumption that the data of each OBH contain a constant but unknown bias, and under the condition that the sum of the squares of the biases are minimized, results in exactly the same regression lines shown in the figure with somewhat smaller variances. This result is due to the mathematics and not to any unique property of the data.

### Conclusions

Data collected by a 1500 km OBH array deployed for two months in the Northwestern Pacific Basin near Wake Island has provided important new information about the propagation of \( Po/So \) phases. Using this array, propagation velocities of first arrivals from shallow-focus (<100 km)
Table 2. Attenuation of Po and So as a Function of Frequency and Propagation Distance

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>Po</th>
<th>So</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-11.5 ± 8.4</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-15.4 ± 6.1</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-18.5 ± 4.7</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-18.4 ± 5.6</td>
<td>-22.4 ± 4.3</td>
</tr>
<tr>
<td>6</td>
<td>-18.3 ± 5.4</td>
<td>-22.3 ± 2.6</td>
</tr>
<tr>
<td>7</td>
<td>-23.4 ± 3.8</td>
<td>-22.3 ± 2.8</td>
</tr>
<tr>
<td>8</td>
<td>-21.1 ± 4.6</td>
<td>-23.4 ± 3.4</td>
</tr>
<tr>
<td>9</td>
<td>-20.6 ± 5.1</td>
<td>-23.4 ± 4.1</td>
</tr>
<tr>
<td>10</td>
<td>-22.1 ± 6.7</td>
<td>-24.7 ± 4.8</td>
</tr>
<tr>
<td>11</td>
<td>-23.4 ± 6.0</td>
<td>-25.9 ± 4.9</td>
</tr>
<tr>
<td>12</td>
<td>-21.0 ± 5.2</td>
<td>-23.3 ± 4.3</td>
</tr>
<tr>
<td>13</td>
<td>-22.2 ± 4.8</td>
<td>-24.8 ± 5.1</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>-23.1 ± 5.2</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>-23.8 ± 5.0</td>
</tr>
</tbody>
</table>
Figure 10. Spectral amplitudes at each frequency studied (Po: 2-13 Hz and So: 5-15 Hz) are plotted versus epicentral distance after modification by zero-meaning as explained in the text. The five data clusters represent the five OBH's used. Note that the data of both Po and So, at all frequencies, follow the same general trend, which is attenuation as a function of distance. For reference, attenuation as a function of distance at each individual frequency in Po and So is listed in Table 2.
events have been measured by a more accurate method than was previously possible using single station data. The velocities found are 7.96 ± 0.05 km/sec and 4.57 ± 0.04 km/sec for Po and So, respectively. measured at epicentral distances between 18°(2000 km) and 33°(3700 km). Associated with these propagation velocities in the linear travel-time equation are intercepts equal to -7.14 ± 2.38 sec and -14.03 ± 5.31 sec for Po and So, respectively. These large negative intercepts imply higher propagation velocities over some part of the travel path nearer to the source than where the data were recorded. Travel times of all Po/So first arrivals collected by HIG since 1963, from shallow-focus events with Northwestern Pacific Basin travel paths greater than 12° epicentral distance, are successfully modeled by the linear travel-time equation: \( T = X/V + I \), using those values for \( V \) (propagation velocity) and \( I \) (travel-time intercept) reported here. Data at epicentral distances less than 12° (collected prior to this experiment) appear to follow a different Po/So travel-time branch than the one described by the OBH data. The exact nature of this branch is not clear due to deficiencies in the quantity and quality of this data. Additional insight into this transition may be found through the examination of Po/So arrivals from numerous deeper-focus events (up to 600 km focal depth) which have been recorded but not yet studied. The OBH data have also been used to directly measure the attenuation of Po and So. An event which occurred in the Kuril Islands (mb=6.6, h=45 km) and generated Po and So arrivals which propagated almost exactly down the axis of the array, was used to quantify attenuation in terms of a frequency-dependent \( Q \). Values found for \( Q(f) \) range from 625 ± 469 at 2 Hz to 2106 ± 473 at 13 Hz for Po, and from 1401 ± 296 at 5 Hz to 3953 ± 863 at 15 Hz for So. This attenuation may be more simply described in terms of the single value -21.5 ± 0.9 decibels per 1000 km of travel path, which in general applies to all the frequencies studied in both Po and So.
Spectral analyses of high-frequency Pn Sn phases from very shallow focus earthquakes (U) Hawaii Inst of Geophysics Honolulu D A Walker Sep 83 AFOSR-TR-84-0059
Acknowledgements. This research was supported by the Office of Naval Research (code 425GG). Funds for support of the hydrophone station at Wake Island were provided primarily by the Air Force Office of Scientific Research under Contract No. F-49620-81-C-0065, with supplementary support from the U.S. Arms Control and Disarmament Agency. The authors express thanks to Dave Byrne, Grant Blackinton, Bob Mitiguy, Dave Barrett, and Fred Duennebier for their help in modifying, testing, launching, and recovering the OBH's. Appreciation is also expressed to Al David and Kentron Corporation for their part in maintaining the recording station at Wake. The authors also thank George Sutton for reviewing this manuscript and Rita Pujaslet for editorial assistance. Hawaii Institute of Geophysics Contribution No. 0000.
References


6 September 1982; 01:47:02; 29.3N, 140.3E; 6,6 MB; 167 Km; South of Honshu; Distance = 25.2°
The purpose of OPA, the newsletter of the "Ocean P Alliance," is to stimulate interest in a seismic phase known as "Ocean P." This phase, Po, and its associated S phase, So, were first observed in the North Atlantic and have since been found throughout the North, Western, and Central Pacific. First arriving Po/So phases travel with fairly constant apparent velocities of about 8.0 and 4.6 km/sec, respectively, while peak arrivals have velocities (about 7.6 and 4.5 km/sec) comparable to basal crustal rates. At distances of about 180° (~2000 km), observed frequencies of Po and So are as high as 30 and 35 Hz, respectively; and at distances of about 300°, as high as 15 and 20 Hz, respectively. The signal-to-noise ratios for Po/So phases are generally at least ten times greater than the ratios of their respective normal, mantle-refracted P and S phases; and, in many instances no P's and S's can be found in spite of the presence of very strong Po's and So's.

Aside from the SOFAR channel of the world's oceans, the Po/So waveguide appears to be the earth's most efficient acoustical waveguide (estimates of Q are as high as 20,000). Also it seems probable that the phenomenon is a dominant feature of all of the world's oceans and marginal seas.

In spite of these remarkable and extensive observations, Po/So research has not yet received the general recognition, interest, and support that it deserves. Recent observations indicate the phenomenon is not just of interest in terms of basic science, but applied science as well. The applied aspects include the detection and discrimination of underground nuclear explosions along subduction zones and/or continental margins, large-scale mapping of the crust and uppermost mantle of the world's oceans and marginal seas, and acoustical studies of ocean sediments and crust at high frequencies.

In view of the foregoing discussions, the intent of this newsletter is to promote interest in Po/So research by providing an additional, and more effective, forum for the exchange of observations and ideas. Contributions or correspondence should be addressed to:

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Acknowledgments. The concept of a newsletter to improve communications among those interested in Po/So research grew directly out of responses to my 30 March letter. I thank all of those who provided this encouragement. I would also like to express my appreciation to a few visionary program managers at the National Science Foundation, the Office of Naval Research, the Air Force Office of Scientific Research, and the U.S. Arms Control and Disarmament Agency.

Dear Potential Ocean P Alliance Members:

On 30 March 1982, I wrote a rather lengthy letter to some of you concerning seismic phases variously referred to as high-frequency Pn/Sn, long-range Pn/Sn, or Ph.f./Sh.f. It was, and is, my opinion that the level of interest in, and support for, research on these phases was far less than commensurate with their potential importance to geophysics. [In the event that your may have misplaced the 30 March letter, some of the more significant observations are summarized in the masthead.] To share this concern and to obtain an objective assessment, I requested that you reciprocate and express your views to me.

As you may have guessed, the response has been very encouraging—so much so that you have before you a new means for the exchange of observations and ideas on the phenomenon of "high-frequency Pn/Sn" propagation.

Rationale. The history of research on these phases since they were first recognized nearly fifty years ago could best be described as sporadic—with only a small number (often zero) of researchers actively studying the phenomenon at any given time. Such efforts for those early years are understandable. Unfortunately, even with the advent of ocean-bottom hydrophones, digital systems which greatly facilitate spectral analyses, and rapidly evolving computer techniques for modeling complex seismic phases, the number of researchers actively studying the phenomenon is still small. As a result much of what we publish is given little attention, or is totally ignored; and this situation is exacerbated by the large number of journals ("haystacks") in which these studies ("needles") can be published.

Thus, the timing now seems appropriate for building a larger constituency and pushing for a solution. Legitimate means are increased communications, as well as continuing quality research. Without such an effort at this time, I am fearful that research on the phenomenon will still be dangerously close to the "sporadic mode," making hard times and additional periods of dormancy very real possibilities.

I believe the assessment that high-frequency Pn/Sn propagation is "a challenge remaining to the theoretician," (Richards, 1979, Rev. Geophys. Space Phys., 17, 312-328) and is "the challenge to both explosion and earthquake seismology for the coming decade" (Hirn et al., 1973, Z. Geophys., 39, 363-384). I also believe that the opportunities for widespread participation in the solution of major geophysical problems are increasingly rare and that such opportunities should be seized.

Name Change. It may be advantageous at this time to suggest that a new name be given to the high-frequency compressional and shear phases observed at great distances in the world's oceans.
difficulty with the nomenclature used to date is that: (1) an, as yet, unsubstantiated relationship to the well known longer-period Pn/Sn phases of continents is inferred; and (2) the environmental feature most strongly linked to the observations is not cited. Thus, a more logical term would be "Ocean P" or "Ocean S" with the abbreviations being "Po/So." With this change, those unfamiliar with the phenomenon would not be as likely to make the false assumption that the phases are similar to continental Pn and Sn. Such assumptions in the past have been a major stumbling block in stimulating interest and support for "Po/So" research.

Our Birthday. You may have noticed something special about the date of this inaugural newsletter—15 September 1982 commemorates the 47th anniversary of the first known published report of Po/So phases.

"In the bulletin of the Harvard Seismograph Station, under date of September 15, 1935, attention was directed to the unusual character of certain records from the vicinity of 17°N, 62°W. One of the novel features was a short-period phase about 23 minutes after P. It has become known as T, for third, with P and S constituting the first and second groups of short-period waves of similar general appearance. The problem was discussed with Weston, and since that time those two stations have been working on it. Linehan published in 1940 the first description outside station bulletin." [Leet et al., 1951, Bull. Seismol. Soc. Am., 41, 129-141].

"At the 1939 meeting of the Eastern Section of the Seismological Society of America, the author presented a paper on earthquakes occurring about 15° to 30° distance from Weston, Massachusetts. The difficulty of locating these quakes was stressed in the paper, due to the strange characteristics of the recordings. Observers of many stations thought of them as a series of locals. As has been mentioned, the records from this area are quite different from those we have recorded from other locations. The predominant characteristic is the multiplicity of their extremely short period. The so-called P-group may last as long as three or four minutes due to the multiplicity mentioned and frequently runs into the S-group: The second group lasts about the same length of time as the former. About 20 minutes after the P-group is a third unidentified group which we have labelled as T." [Linehan, 1940, EOS Trans. AGU, 21, 229-232].

"Actually, many features of P and S are abnormal on this and later records from certain areas at this distance range, and work on that part of the problem is in progress, but the investigation of T has been undertaken first." [Leet et al., op. cit.]

As I stated in my 30 March letter, although the T-phase was accurately identified in a relatively short time as compressional energy traveling in the sound channel of the world's oceans, one could best describe work on the other "part of the problem" (i.e., the "abnormal" P and S phases), 47 years later, as still being "in progress."

It is my hope that on the 50th anniversary of the first reported observations of Po and So, the need for a special newsletter would no longer exist.

Success. The minimum objective of the newsletter is nothing more than the stimulation of deserved interest in Po/So research. Achievements beyond the minimum objective will be strongly dependent on contributions and correspondence from members and their "lobbying efforts" with program managers.

Membership. The "Ocean P Alliance" is not at the moment a formal organization. If no useful purpose would be achieved by "formalization" then this current status should remain unchanged. Anyone wishing to be considered as a member of the Alliance is automatically "in." Anyone wishing to remain skeptical, but nonetheless interested, could consider themselves, if they wish as non-members and still receive the newsletter. I may at some later date directly ask you for your opinions on the newsletter.

I would hope that those receiving the newsletter would provide: (1) The names and addresses of individuals who should be added to our mailing list, and (2) Po/So publications which should be added to our Po/So bibliography, as well as news of forthcoming publications. If you have some other newsworthy items or comments on topics discussed in OPA, please send them to me. I would also like to know if you have been mistakenly placed on the mailing list.

Format. We hope that you will have all issues of OPA for future reference. To that end we have a format conducive to storage in a 3-hole binder.

Future Topics. Items for future issues include the OPA mailing list, correspondence from members, a bibliography of Po/So research, more amazing Po/So recordings, news of upcoming publications, and interesting questions for debate.

Our Covers. To further commemorate the first reported observation of Po, So, and T phases in September of 1935 across the North Atlantic Basin, we have covered our newsletter with Po, So, and T phases which were generated in September of 1982 across the Northwestern Pacific Basin. In addition, the normal, mantle-refracted P is also shown. These phases were recorded on a twelve channel hydrophone array located near Wake Island. Do you see any similarities between these Pacific phases and those from the Atlantic discussed by Leet et al. (op.cit) and Linehan (op. cit.)? What significant observations can be made from these plots? For answers, "tune in" to the next issue of OPA!

Dan Walker
Event 14
27.2°

Event 17
29.4°

Event 18
32.7°
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Dear Colleague:

As you may recall, the covers for our inaugural issue consisted of a digitally rectified and compressed plot of P, Po, So, and T phases for an earthquake south of Japan recorded by the Wake hydrophones (front cover) and spectrums for these same phases (back cover). For purposes of the discussion which will follow these figures are repeated here in a severely reduced form. In closing the inaugural issue, I asked whether you could see any similarities between these Pacific phases and those from the Atlantic discussed by Leet, Linehan, and Berger (1951) and Linehan (1940). The unusual characteristics mentioned by these authors are the similar general appearance of their so-called P (primary) and S (secondary) groups to the later arriving T (tertiary) group, the multiplicity of their extremely short period with the P frequently running into the S group, and S about as long as P.

Certainly all of these characteristics have been seen in the Pacific as exemplified in the figures shown here. The P, S, and T groups are of the same general appearance, the P group runs into the S group, in some respects the S group may be about as long as P, and the phases are of extremely short period. The striking and remarkable similarities of these phases are most evident in the spectrums, which also serve to quantify their short period content.

6 September 1962; 00:17-02:29.1.14D.3E; 6.5 Mw. 187 HT. SOUTH OF HONOLULU. DISTANCE = 25.2°
The T Phase: A New Approach to Po/So Research. Especially intriguing is the detailed correlation of the T spectrum to the So spectrum. This and the general correlation of the T and Po spectra suggests a possible new approach to Po/So research. It is now appropriate to consider the possible relationship of Po and so t to T. Other evidence suggesting a possible relationship of Po and so to T is contained in the report "Oceanic Po/So Phases: A Qualitative Explanation and Reinterpretation of the T-Phase" (D. Walker, HIG Report 82-6, 1982). [Topics from this report are discussed in this newsletter].

Spectra for Atlantic Po, So, and T Phases: A Challenge for East and Gulf Coast Seismologists. I believe that Leet, Linehan, and Berger would be surprised at just how short the periods were for the phases they observed. Unfortunately, the recordings and instrumentation which they had (in all probability 60 mm/minute analog recordings from standard 1 Hz instrumentation) did not permit them to see just how high the frequencies were. In the deep ocean near Wake, forty years later, we have the advantages of lower noise in the 3 Hz to 15 Hz range than most continental stations, a better system response to those frequencies than conventional 1 Hz instrumentation, digital recordings, and computers which facilitate the derivation of spectra. It is nonetheless surprising that spectra of Atlantic Po, So, and T phases have not been published. (If I am mistaken, I hope someone will write and provide references.) It would be interesting to compare these spectra to those from the Pacific. I hope that some east or Gulf Coast seismologists will take the challenge and be the first to quantify the frequency content of Atlantic Po/So phases.

Continuing Japanese Research on Po/So. I was pleased to meet recently with Drs. Nagumo and Kasahara and to review a preprint of their new paper, with Drs. Ouchi and Eroshin, on OBS observations of Po/So phases. The report contains important information on Po/So velocities. I wish them every success in efforts to publish this important paper.

Po/So Bibliography. One of the major objectives of the OPA Newsletter is to acquire a comprehensive and up-to-date bibliography of Po/So research. A preliminary attempt to achieve this objective follows. I hope that readers aware of omissions will bring them to my attention so that they can be added to the listings.

Our Covers: How you see "it"? How you don't! The covers are spectrograms from the Wake Island hydrophones. Expected times of arrivals are based on either the Jeffreys-Bullen tables for F or Po/So travel time curves. The contour interval is 8 db. The line at 10 Hz is due to time code cross talk.

What's "it"? The So - very strong on the front cover, but weak or absent on the back cover. Phases shown on the front cover are typical of events from the Japan, Kuril, Kamchatka portion of the circum-Pacific arc; and, therefore, these phases have travel paths to Wake under the deep Northwestern Pacific Basin. Phases shown on the back cover are typical of events from the New Ireland and Solomon Islands area; and, therefore, these phases have travel paths to Wake under the shallow Ontong-Java Plateau as well as portions of the deep Northwestern Pacific Basin.

An obvious explanation is differences in source characteristics. Unfortunately, this seemingly reasonable explanation cannot be correct, since So phases from the New Ireland and Solomon Islands area are well recorded at Ponape on the northern margin of the Ontong-Java Plateau (roughly mid-way between the source locations and the receivers at Wake). [Of the more than forty events from the New Ireland and Solomon Island area recorded at Ponape during an approximate seventeen month experiment, amplitudes of So phases are at least comparable to, and frequently larger than, those of their respective Po phases.]

What, then, could be the explanation? Possible clues are: (1) the transition in shallow Ontong-Java Plateau to the deeper Northwestern Basin; and (2) the frequent absence or weakness of So, presence of Po, at great distances (often more
than 4000 km) throughout the North Pacific (Walker, 1977a and b) and Central Pacific (Talandier and Bouchon, 1979), in spite of stronger So's than Po's for relatively homogeneous travel paths across the deep Northwestern Pacific Basin.

A possible explanation will be given in the next issue of OPA. Please send any comments or suggestions on this or other items.

Po/So Bibliography


Bennazani, M., B. Isacks, and J. Oliver, 1972, Propagation of seismic waves through and beneath the lithosphere that descends under the Tonga Island arc, J. Geophys. Res., 27, 952-958.


Kusanaha, B., and R. Harvey, 1977, Seismological evidence for the high-velocity zone in the Kuril trench area from ocean bottom seismometer observations, J. Geophys. Res., 82, 3005-3014.


Linehan, D., 1940, Earthquakes in the West Indian region, BOS Trans. AGU, 22, 279-273.


Talandier, J., and M. Bouchez, 1979, Propagation of high frequency Pn waves at great distances in the Central and South Pacific and its implications for the structure of the lower lithosphere, J. Geophys. Res., 84, 5613-5619.


APPENDIX VIII
The purpose of OPA, the newsletter of the "Ocean P Alliance," is to stimulate interest in a seismic phase known as "Ocean P." This phase, Po, and its associated S phase, So, were first observed in the North Atlantic and have since been found throughout the North, Western, and Central Pacific. First arriving Po/So phases travel with fairly constant apparent velocities of about 8.0 and 4.6 km/sec, respectively, while peak arrivals have velocities (about 7.6 and 4.3 km/sec) comparable to baseline crustal rates. At distances of about 10° (2000 km), observed frequencies of Po and So are as high as 30 and 35 Hz, respectively; and at distances of about 30°, as high as 13 and 20 Hz, respectively. The signal-to-noise ratios for Po/So phases are generally at least ten times greater than the ratios of their respective normal, mantle-refracted P and S phases; and, in many instances, no P's and S's can be found in spite of the presence of very strong Po's and So's.

Aside from the SOFar channel of the world's oceans, the Po/So waveguide appears to be the earth's most efficient acoustical waveguide (estimates of Q are as high as 20,000). Also it seems probable that the phenomenon is a dominant feature of all of the world's oceans and marginal seas.

In spite of these remarkable and extensive observations, Po/So research has not yet received the general recognition, interest, and support that it deserves. Recent observations indicate the phenomenon is not just of interest in terms of basic science, but applied science as well. The applied aspects include the detection and localization of underground nuclear explosions along subduction zones and or continental margins, large-scale mapping of the crust and uppermost mantle of the world's oceans and marginal seas, and acoustical studies of ocean sediments and crust at high frequencies.

In view of the foregoing discussions, the intent of this newsletter is to promote interest in Po/So research by providing an additional, more effective, forum for the exchange of observations and ideas. Contributions or correspondence should be addressed to:

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Views expressed in this publication are those of the authors only and do not reflect official positions of the Ocean P Alliance unless expressly stated.

Dear Colleague:

The covers of our last issue, shown here in reduced form, are spectograms for phases with travel paths to the Wake Island hydrophones under the deep Northwestern Pacific Basin (front cover) and under the shallow Ontong Java Plateau (back cover). An obvious explanation for the absence, or weakness, of So (labeled Sn) on the back cover is differences in source characteristics. However, recordings made during an earlier experiment at Fomaps, roughly midway between the receivers at Wake and the source locations of earthquakes in the New Ireland and Solomon Island areas (see accompanying map), indicate that this explanation can not be correct. Over an approximate seventeen month recording period, more than forty events from the New Ireland and Solomon Island area were recorded, with the amplitudes of So at least comparable to, and frequently larger than, those of their respective Po phases.

An observation which contributes to a possible explanation is the frequent absence or weakness of So, yet presence of Po, at great distances (often more than 4000 km) throughout the North Pacific (Walker, 1977a and b) and Central Pacific (Talander and Bouchon, 1979), in spite of stronger So's than Po's for relatively homogeneous travel paths across the deep Northwestern Pacific Basin.
The explanation arising from these observations, then, is that paths other than those across relatively homogeneous ocean basins are likely to encounter large lateral changes in the crust and upper mantle. Observations require that the changes be such that Po signal strength is reduced without seriously affecting the So phase. Large lateral changes could be produced by plateaus, rises, ridge systems, island and seamount chains, fracture zones, transform faults, fossil arc and trenches, and rafted continental fragments. The transition from the shallow Ontong Java Plateau to the deeper Northwestern Pacific Basin (see accompanying figures), as well as the extension of the Caroline Archipelago through this region, could be features responsible for the weak, or absent, So at Wake from events in the New Zealand and Solomon Island area. [This interpretation has been taken from a recent attempt (Walker, 1982) to provide a qualitative framework consistent with all of the diverse observational aspects of Po/So—hoping that this would eventually lead to comprehensive and detailed quantitative analyses and, ultimately, a generally acceptable model for the generation and propagation of Po/So.]

**Nuclear Connections.** In the masthead of this newsletter, reference is made to Po/So being of interest in terms of the detection and discrimination of underground nuclear explosions. It may be worthwhile at this time to be more explicit as to possible reasons for such interest.

A. **Obvious - Large S/N Ratios for Po/So.** An examination of the covers of previous OPA newsletters is all that is needed to suggest that S/N ratios for Po/So may be larger than the ratios for mantle refracted P (S is not generally apparent for distances of up to about 20°). Indeed, numerous observations from the deep ocean, as well as hard rock island sites, in the Western Pacific indicate the S/N ratios for Po/So at their dominant frequencies (about 4 to 8 Hz) are generally from 5 to 10X greater than the S/N ratios for P at its dominant frequencies (about 1.5 to 2.5 Hz). This dominance may extend out to distances of 3000 km, with P increasing in strength relative to Po/So beyond this range. Also, at distances less than about 20°, the travel times of Po phases are such that they may arrive ahead of the mantle refracted P, thus masking whatever P energy may be present.

Although some of the most extensive observations of Po/So phases have been in the Western Pacific, these phases have also been observed in other portions of the Pacific and the North Atlantic. The nature and extent of those observations suggest that the phenomenon could be a dominant feature of all the world's oceans and marginal seas.

Thus regional detection and discrimination of underground explosions with seismic instrumentation in an ocean environment (island, the water column, bottom, or sub-bottom) may be based on Po/So recorders.

As to why detection and discrimination in an ocean environment should be important, one has only to look at a globe. As to whether, in fact, detection and discrimination in an ocean environment is important, one has only to consider recent investments in ocean-sub-bottom seismometers.

B. **Less Obvious - Lg/Pg Comparison.** Just as Po/So are the most prominent phases recorded at regional distances for oceanic travel paths, Lg and Pg are prominent phases recorded at regional distances for continental travel paths. Certainly Lg/Pg are of great importance in regional detection using continental stations (just as Po/So should be of great importance in regional detection using oceanic stations). Surprisingly, the much studied phenomenon of Lg/Pg suffers problems of understanding not unlike those associated with Po/So. In a recent publication (1983) Gupta and Blandford state: "The mechanism for the generation of transverse component motion from explosions is still not clearly understood in spite of the large number of studies on the subject." [p. 571] and "... no convincing explanation has so far been offered for the generation of short-period (about 1 sec or less) transverse motion from explosions." [p. 572.]

[In their report they propose a scattering mechanism for the generation of short period transverse motion (including Lg) from explosions.]

Regarding the utility of Lg/Pg in the discrimination of nuclear explosions, several theoretical studies suggest a strong dependence of Lg/Pg signal character on focal depth. Also, Gupta and Blandford note that "the observed differences in the spectra of shear waves
(i.e., Lg) from explosions and earthquakes seem to be large enough to be useful for source discrimination" [p. 589].

Could it be that Lg/Pg investigators might better understand certain aspects of Lg/Pg by turning their attention to Po/So? Or, conversely, might Po/So investigators better understand Po/So by turning their attention to Lg/Pg? Because of the thinness and uniformity of the oceanic crust and upper mantle under the deep ocean basin relative to that under large portions of continents, could Po/So be viewed as less adulterated (and, therefore, less complex) forms of Lg/Pg? And, finally, could comparative studies of Lg/Pg and Po/So lead to important breakthroughs in detection and discrimination capabilities on continents and in the oceans?

In my opinion all of these questions are very important. If you share this view, I hope that you will bring the phenomena of Po/So to the attention of your associates who may be working on Lg/Pg. I am happy to report that at least one organization (Rondout Associates Incorporated) has recognized the potential of comparative studies between Po/So and Lg/Pg in the form of a research proposal submitted to AFOSR. [Indeed, most of my views on this topic were based on discussions presented in that proposal.]

C. Indication - Mantle Refracted Explosion P's. Our front cover is a plot of estimated ocean bottom background noise (shaded region "A") near Wake Island compared to other measurements. [A detailed description of this figure is given at the end of the newsletter.] It is apparent from this plot that the noise levels near Wake for frequencies from about 3 to 15 Hz are comparable to, or better than, those for almost all of the other continental sites. This would be of little significance if there were no signals at these frequencies. However, by some fortuitous accident of nature (my apologies to those of you who may be new to the field), Po/So phases (as has already been mentioned) have strong signals in the 4 to 8 Hz range. Further complicating this accident, (a) mantle-refracted P phases from underground nuclear explosions recorded at great distances (i.e., at distances from about 60° to 90°) have surprisingly large amounts of energy at frequencies above 3 Hz, with higher corner frequencies than earthquakes at comparable distances; (b) explosions with smaller yields are believed to be relatively richer at higher frequencies; (c) the Wake hydrophones are ideally located in the 60° to 90° distance range from most of the known nuclear test sites (see accompanying figure: the shaded area represents the 60° to 90° distance range; solid circles represent underground nuclear test sites; the 90° boundary is firm since no P energy is observed beyond this distance; the 60° boundary is not firm since high frequency P energy has been observed at shorter distances); and, (d) ocean surce reflections can be used in signal enhancement (see back cover; a thorough description of this figure is given at the end of the newsletter).

The connection, then, is that sites ideal for the study of Po/So may also be of great value in recording underground explosions at great distances. [More detailed discussions of hydrophone recorded explosion P's may be found in a recent publication by McCreery et al. (1983).]
Comparisons of these spectra, those on the back cover of OPA No. 1 (shown here in reduced form), and the front cover of this newsletter are most interesting. For both sets of spectra, Po's and S0's are well above background noise out to about 10 Hz. The greater B/N ratios recorded on the ocean bottom (Wake hydrophone) at frequencies above 10 Hz may be the result of lower over continental portion of the spectrum. The greater B/N ratios recorded on the ocean bottom (no noise) at frequencies below 1 Hz is almost certainly a result of the lower noise levels of continents at those values. Therefore, the B/N ratios indicated in the spectra do appear to be consistent with the noise curves for continents and oceans shown on the front cover of this newsletter.

It is hoped that the publication of the Atlantic Po/So spectrums is just the beginning of many comparative studies with Pacific Po/So phases (e.g., velocities, spectra, Q's, effects of continental paths, structural interpretations, etc.).

Po/So Bibliography. Some additions to the bibliography published in the last issue of OPA can already be made. Item #1 is a tentative addition since this modeling effort is applicable only down to periods of 3 seconds and no direct references are made to the "Po/So" phases observed at much higher frequencies for oceanic travel paths (i.e., Po/So). Item #3 was mistakenly omitted from the original list.


Our Covers. The front cover shows the average spectrum + 1 standard deviation of 52 samples of background noise over 18 months from the Wake bottom hydrophones (A). Also shown are some published noise curves for both ocean-bottom (B, C, D, and E) and continental (F, G, and H) environments, which have been converted from an assortment of units to the scale shown. B is a hypothetical "sample spectrum of deep-sea noise" (Urish, 1975, p. 186). C is a vertical seismometer measurement made in the Marianas Basin (Aasle and Himmels, 1976). D is a vertical seismometer measurement made at 4.6 km depth between Hawaii and California (Branner and Dodd, 1968). E is a noise curve for a hydrophone bottomed off Kilauea Island at 1200 m depth (Nichols, 1981). E represents low, average, and high noise levels estimated from curves compiled by Brune and Oliver (1959). F is an area bounded by the limits of noise curves measured on vertical seismometers for 36 locations within the United States and Germany (Frantti et al., 1962). G is the noise curve for the Gyer submarine of the Norwegian seismic array measured during a period "when most of the North Atlantic Ocean was very quiet" (Bunge et al., 1971). The back cover shows a sample time series of Po, filtered to maximize signal/noise, from two nuclear explosions recorded on the Wake bottom hydrophones. The upper trace is from a single hydrophone and shows the direct arrival and its first water surface reflection. The lower trace is a composite of signals from two hydrophones with 40 km separation, obtained as follows: the filtered (1.5-5.0 Hz) time series from each hydrophone was inverting, shifted in time by the water surface reflection time, weighted to maximize the increase in signal/noise, and added to itself; the two half-cycling time series were then added with the appropriate propagation delay, and weighted to maximize the increase in signal/noise. Signal/noise was increased by 90% of the theoretical maximum with this method, indicating a high level of coherence between the signals added.

Both covers are discussed elsewhere in the newsletter. An interesting question posed by the front cover is this:

"World instruments with responses comparable to those of the short period components of the World-Wide Seismograph Network (WWSSN) be appropriate for the studies of regional and teleseismic body phases recorded on, or in, the ocean bottom?"
Reminder: You are invited to comment on topics presented in the newsletter and to provide other items of interest. Also, since it is difficult to be aware of all papers published in the many differing geophysical journals, advice on any omissions in the Po/8o bibliography would be appreciated. Again, special thanks to RAI for sharing their Po/8o spectrum with us.

References


APPENDIX IX
The Continuous Digital Data Collection System for the
Wake Island Hydrophones

by

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ABSTRACT

A continuous digital data collection system was installed on Wake Island in August, 1982, to record seismic signals from an array of nearby hydrophones. Most of the hardware has been purchased "off-the-shelf" from various nationally known vendors. A few components have been built at the Hawaii Institute of Geophysics (HIG). Software for both the data collection and data reduction has been written at HIG. Some key features of the data collection system are: 1) 96 dB dynamic range (i.e., 16 bits), 2) up to 16 data channels, 3) accurate absolute timing (+1 msec, generally), 4) accurate interchannel timing, 5) power-failure recoverability, 6) up to 80 samples per second per channel (variable), 7) ease of operation (only four operator commands necessary), 8) operator intervention only once per day (to change up to 4 full reels of 9 track tape), and 9) common tape format (blocked data, 2 bytes per word, 2's complement notation). The preliminary data reduction consists of: 1) stripping off intervals of data for which seismic phases from known events are suspected of being present; and 2) stripping off randomly spaced 3-minute intervals (1 per hour on the average) as ambient noise samples. These tasks are accomplished by a series of programs run at HIG on a Harris H800 computer. This paper is primarily intended for the reader who wants to build a digital data acquisition system, or who wants to use the data collected by this particular system at Wake.
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INTRODUCTION

In June, 1979, BIG began operation of a four-channel (3 data, 1 time-code), slow-speed, cassette recording system for continuous monitoring of hydrophones located near Wake Island. The seismic data collected from this system have provided much needed information about ambient noise in the deep ocean, Po/So propagation, and the spectra at high frequencies (i.e., > 2 Hz) of deep mantle P phases from earthquakes and explosions recorded at great distances. However, the recording system itself had limitations which prevented more quantitative types of data analysis. These limitations included: 1) a dynamic recording range of only about 40 dB — this caused many signals to be clipped; 2) poor timing due to clock drift — absolute timing was accurate to only ±0.3 sec.; 3) poor interchannel timing — differences in skew between the recording and playback heads could easily result in a 0.1 sec. timing error between channels; 4) analog format — a sophisticated, time consuming and data degenerating process was necessary to convert the analog signals to digital time series for further processing; and 5) only three of at least eleven working hydrophones could be recorded.

To eliminate these problems, a system was sought with the following general capabilities and constraints: 1) a large dynamic range to record, without distortion, events ranging from at least mb = 4.0 to mb = 8.0 (i.e., at least 80 dB); 2) Absolute timing accurate to less than 0.1 sec (for ease in processing, no time correction should need to be applied to achieve this accuracy); 3) Interchannel timing accurate to within only a small change in phase of the highest frequency of interest (e.g., 0.002 sec for a $\pi/8$ phase change at 30 Hz); 4) a digital recording format such that only a minimal amount of processing is necessary to convert the data to a widely
useable format; 5) the capability to record all eleven available hydrophones; 6) the recording of frequencies at least as high as those already observed at Wake in Po and So (i.e., 30 Hz); 7) operation of the system so simple that it can be accomplished by personnel untrained in computer hardware and software; 8) required servicing (i.e., changing tapes) no more than once per day; and 9) the capability of restarting automatically after power failures (which occur frequently at Wake). After exploring numerous options, a design was chosen which met the specifications outlined above, and also appeared to have the best chance for success in terms of the reliability and intercompatibility of its components and the feasibility of writing the necessary data acquisition software. This system was purchased, assembled, software and tested between March and August, 1982, and was installed at Wake during the last week of August, 1982.

Because of the large volume of raw data which would be collected by this system (i.e., up to 1460 full reel, 9-track, computer tapes per year) a scheme was desired for compressing the data. Data types which were considered the highest priority for saving are: 1) seismic phases applicable to ongoing research topics, 2) ambient noise samples, and 3) seismic phases for future research topics. A system of programs was written to extract and save those intervals in the raw data which contain these priority events. These programs also manage the data for easy accessibility and transmission to other scientists.
RECORDING SYSTEM HARDWARE

The hardware used for the digital recording system is outlined in the flow chart of Fig. 1. The hydrophone signals are first amplified and shaped by the preamps and pre-whitening filters. Two of these signals are filtered further and used to create a helicorder-style seismogram. All of the signals from the preamps are converted to discrete time series by the A/D (analog to digital) convertor. The digitized data is then assembled into blocks and output to the tape drives by the LSI-11/2 computer. The satellite clock provides a time code for the helicorder, a synchronization signal for the A/D sampling pulse generator, and the date and time in digital format for inclusion with the data blocks written to tape. A more detailed description of the function of each component in Fig. 1 is given below:

Wake Hydrophones

The hydrophones are passive, moving-coil type, which are connected via cable to Wake Island. The estimated response is shown in Fig. 2. The hydrophones are located in two arrays. One array contains six sensors on the ocean floor at 5.5 km depth, and has an aperture of 40 km. The other array consists of five hydrophone pairs at SOFAR depth (1 km) and has an aperture of 300 km. Of the ten hydrophones in the SOFAR array, at least five of them at three sites appear to be working.

Preamp/Pre-Whitening Filters (HIC built)

The preamps are designed to have very low intrinsic noise levels because the hydrophone outputs are very small [as small as 10 nVolts/(Hz)$^{1/2}$] at 10 Hz]. The pre-whitening filters are designed to flatten the ambient
Figure 1. A general diagram of the hardware used for the Wake data acquisition system. Each device on QBUS represents a single printed circuit board, and these boards are mounted in the enclosure from top to bottom as shown.
Figure 2. The estimated response of the Wake hydrophones (taken from the Columbia University's OBS Calibration Manual by S. N. Thamos, 1966).
ocean-bottom noise spectrum out of the hydrophone (measured previously using analog data), for the purpose of maximizing the dynamic recording range at all frequencies. Anti-aliasing filters and a 60 Hz notch filter are also included. The output amplifier stage has 10 gain steps (0–9), each 3 dB apart, which can be manually set. The response of the preamp/pre-whitening filters is shown in Fig. 3 (for gain step 9).

A/D Convertor (Data Translation Model DT2784SE/DT5716-B)

The A/D convertor is designed to fit into the backplane of the LSI-11/2 computer (i.e., into QBUS), with a cable and connector for receiving the signals to be digitized. The resolution is 16 bits, giving decimal values between -32,768 and +32,767 for inputs between -10.0 and +10.0 Volts, respectively. Up to 16 single ended inputs are acceptable, and the maximum throughput rate is 2.5 kHz (i.e., a minimum of 0.4 msec between samples). Simultaneous sample and hold of all channels is not available on this board, so the 16 channels are sampled sequentially. Furthermore, the design of this device actually requires that all 16 channels be sampled sequentially; the data of unwanted channels being discarded by the software. The trigger which causes a sample to be taken is provided externally by the A/D sampling pulse generator. An example of the temporal spacing between data points which is created by this scheme is shown in Fig. 4. Digital output from the A/D convertor is loaded directly into the LSI-11/2 core memory via direct memory access (DMA).

Satellite Clock (Kinematics model 460 DC)

The satellite clock provides inexpensive accurate time at a remote site by monitoring signals from the GOES satellites (East or West). Accuracy is
Figure 3. The response of the preamp/pre-whitening filters at gain step 9 (of 0-9). Subtract 3 dB from the amplitude response for each gain step down from 9.
Figure 4. An example of the temporal spacing between data channels created by the data acquisition hardware and software for a sampling rate of 80 samples/second/channel. Hydrophones numbered 0 (also starred, *) are for unwanted data channels which are sampled by the A/D convertor but later discarded by the WAKEUP software. This channel/hydrophone information is written into the header part of each data block. The configuration shown is one which has been in use since the system was installed.
better than +1 msec when the satellite signal is being received. The time, in Julian days through milliseconds, is output in parallel BCD format through 45 pins of a 50 pin connector. This connector also contains 4 pins for the clock status (i.e., the worst case clock accuracy based on the amount of time since satellite synchronization was lost), and 1 pin with a 1 kHz square-wave used to determine when the other pins can be read (i.e., are not changing states). Also output (on BNC connectors) are a 1 Hz square-wave used to synchronize A/D sampling with the clock, and a slow code used for marking time on the helicorder record.

**A/D Sampling Pulse Generator (HIG built)**

This device is used to create precisely timed pulses (downward zero-crossings) which are synchronized with the satellite clock and trigger A/D conversions. The front panel has thumbwheel selectors for setting the number of channels of data to be sampled (always 16 in this system due to the A/D convertor; software discards unwanted channels), and the sampling rate (in samples/sec/channel). For 16 channels of data, sampled at 80 samples/sec/channel, the pulse generator produces a 1280 Hz square-wave. A/D synchronization with the clock is necessary so that the starting times of output data blocks, which are assembled for a constant number of A/D conversions, will also remain synchronized over long periods of time.

**Mounting Enclosure (DEC model BALI-NE)**

The mounting enclosure contains the power supply, backplane (QBUS), and cooling fan for the LSI-11/2 computer. The backplane has quad connectors for nine boards, all of which are occupied in this system configuration.
These nine boards, and the order in which they are placed from top to bottom in the enclosure, are noted in Fig. 1.

**LSI-11/2 Computer (DEC model KD11-BA)**

This is the central processing unit of the computer.

**64 K-byte memory (DEC model MSV11-DD)**

This is the core memory for the computer, consisting of 32K 2-byte words.

**Bootstrap module (DEC model BDV11-AA)**

This module brings up the computer from a down or power fail status, and causes the RT-11 operating system to be loaded from the disk.

**64 Bit I/O Controller (DEC model DRV11-J)**

This board is necessary to interface the LSI-11/2 with the 50 pin output of the satellite clock. The 64 bits of I/O correspond to four two-byte words which may be accessed by the software to read the clock.

**Floppy Disk Drive Controller (DEC model RXV21-BA)**

This board interfaces the disk drive to the computer.

**Dual 512K Byte Floppy Disk Drive (DEC model RXV21-BA)**

The floppy disks contain all of the software necessary for performing data acquisition with the hardware. Under the present configuration, one disk contains the DEC RT-11 operating system software, while the other disk contains the programs written at BIG for collecting the data and a
parameters file which describes the exact configuration to be run (i.e., number of channels of data, blocksize, etc.). It is possible, should one disk drive become faulty, to combine all of the programs and data on one disk, and run from a single drive. A special function of the disk drive is to record the number of the current tape drive to which the data are being written. In the case of a power failure, which causes the core memory of the LSI-11/2 to be lost, the current tape drive number is necessary to safely and efficiently resume recording.

**ETA Line Controller (DEC model DLV11-J)**

This device provides four ports (0 to 3) for serial I/O (RS-232C, RS-422, or RS-423) to the LSI-11/2. Port 3 is the only one in use under the current operating configuration and interfaces to the DEC LA38-GA which is serving as both a line printer and operator console at 300 baud. Separate ports for the line printer and a CRT operator console were used during program development to facilitate higher baud rates.

**Console and Printer (DEC model LA38-GA)**

This device is used for all operator input and output (I/O) with the system, and for all program messages. Since there is actually very little I/O to this device, its slow speed is not a problem. Also, there is a distinct advantage in having a hardcopy record of certain essential I/O, especially since the system is at a remote site. Sample I/O is shown in Fig. 5.

**Tape Controller and Formatter (DATUM model 15221)**
### Wake Hydrophone Array Continuous Digital Seismic Recording System

**Using Drive 2**  
**Date** 1983:153  
**Time** 08:06:00:000  
**Clock** 00

**Using Tape**  
**Drive 2 End of Tape Reached**  
05820 Blocks Written

**Using Drive 3**  
**Date** 1983:153  
**Time** 10:59:999  
**Clock** 00

**Using Tape**  
**Drive 3 End of Tape Reached**  
05824 Blocks Written

**Drive 0 Offline**

**Using Drive 3**  
**Date** 1983:154  
**Time** 00:19:999  
**Clock** 00

**Using Tape**  
**Switch Drives**  
**Drive 1** 05217 Blocks Written

---

### Wake Hydrophone Array Continuous Digital Seismic Recording System

**Using Drive 2**  
**Date** 1983:154  
**Time** 07:31:04:999  
**Clock** 00

**Using Tape**  
**Drive 2 End of Tape Reached**  
05824 Blocks Written

**Using Drive 3**  
**Date** 1983:154  
**Time** 15:24:999  
**Clock** 00

**Using Tape**  
**Drive 3 End of Tape Reached**  
05804 Blocks Written

**Drive 0 Offline**

**Using Drive 1**

**Using Tape**  
**Date** 1983:154  
**Time** 23:04:999  
**Clock** 00

**Reset-Wait for Minute**

**Drive 1** 06065 Blocks Written

---

### Wake Hydrophone Array Continuous Digital Seismic Recording System

**Using Drive 2**  
**Date** 1983:155  
**Time** 11:06:000  
**Clock** 00

**Using Tape**  
**Drive 2 End of Tape Reached**  
05822 Blocks Written

**Using Drive 3**  
**Date** 1983:155  
**Time** 16:10:000  
**Clock** 00

**Using Tape**  
**Drive 3 End of Tape Reached**  
05807 Blocks Written

**Drive 0 Offline**

**Using Drive 1**

**Using Tape**  
**Date** 1983:156  
**Time** 20:05:000  
**Clock** 00

**Switch Drives**  
**Drive 1** 05063 Blocks Written

---

Figure 5. A sample of 3 consecutive days of I/O through the console at Wake. Operator input has been underlined (S, R, and S). The operator writes-in the WAKEUP tape identification numbers.
The tape controller interfaces the tape drives with the LSI-11/2. Only one controller is necessary for the four tape drives used. The formatter encodes the blocks of data written to tape, and decodes the blocks read from the tape. Only one formatter is necessary for the four tape drives.

**Tape Drives (DATUM model D451)**

Four 1600 bpi tape drives (0-3) are available for writing out the digitized data. Data is written to one drive until its tape is full (or until a specified number of blocks have been written), then data is written to the next drive in the sequence until its tape is full, and so on. Four tape drives are required if tapes are changed only once per day, since one day's data (11 channels at 80 samples/sec/channel) fills four tapes. An important feature which these tape drives have, is that they re-tension the tape, advance the tape several inches for safety, and put themselves "on line" after a power failure. This is an important factor which allows the system to start collecting data again without operator intervention or the unnecessary loss of data.

**2-5 Hz Filter (HIG built)**

The two-channel 2-5 Hz bandpass filter is for filtering the two signals going to the drum recorder in a way which enhances signal to noise ratios of teleseismic P from underground nuclear tests. The filters are a two-pole passive RC design with the response shown in Fig. 6.
Figure 6. Response curve for the 2-5 Hz filter which precede the holocorder.
This equipment is used to provide easily scannable visible records of the continuous seismic data. The recorder has two pens for the two input signals, and is geared so that one recording sheet lasts 24 hours. Additionally, the amplifiers and drum recorder are powered by a trickle charged, automobile battery backup system to provide continuous operation through power failures. Time code is input from the satellite clock. A sample helicorder record is shown in Fig. 7.

CONTINUOUS DATA ACQUISITION SOFTWARE

The data acquisition program, titled WAKEUP, is written in assembler code and executed under the RT-11 operating system. A simplified flow chart of this software is shown in Fig. 8. Some key features of program WAKEUP are: 1) it is controlled by an input parameters file which can be changed to satisfy differing data collection requirements; 2) it is extremely simple to run — only four, one-letter, operator commands (to be discussed later) are recognized; 3) it can restart itself after a power failure; and 4) it makes a hardcopy log of important program events.

WAKEUP Parameters

The WAKEUP running parameters can be displayed and changed by an interactive fortran program called PARAMS. A sample run of PARAMS is shown in Fig. 9. The parameters and their meanings are described below:

Digitization Rate. The value set here should be the same as the value set on the A/D sampling pulse generator for samples/sec/channel.
Figure 7. A section of helicorder record from Wake showing the P arrival from an Eastern Kazakh explosion (the impulsive arrival) and some other unidentified arrivals which are probably T-phases. There are 30 minutes between each trace.
Figure 8. Generalized logic flow-chart of program WAKEUP which controls the data acquisition. The program is started either manually, or automatically after a power failure. The A/D converter interrupt has a high priority and is serviced immediately. The operator command interrupts are low-priority and are serviced when the CPU is in the wait (W) condition. Paths marked S, R, T, or D are followed (only once) after the corresponding operator interrupt is serviced. Three data buffers are used; two of them provide a double buffer for DMA output from the A/D converter, and the third is used for assembling the data block to be output to tape.
Figure 9. A sample run of program PARMS which is used to change (or view) the running parameters of program WAKEUP. These parameters are stored on disk files DK:WKPARM.BIN and DK:RCOVRY.BIN. Operator commands have been underlined.
Seconds Per Tape Block. This value, multiplied by the sampling rate and by
the number of active data channels, will determine the total number of
samples per block. The number of samples per block should not exceed
5000 due to size limitations in the core memory containing the buffers.
Very small block sizes should also be avoided, since the time to write a
very small block to tape may exceed the time necessary to collect the
data block.

Channel Number (CH). This is not a changeable parameter, but merely
indicates which channel (0-15), of the A/D convertor, is being referred
to.

Hydrophone (HYD). This parameter indicates which hydrophone (71-76 for the
bottom array, and 10, 11, 20, 21, 40, and 41 for the SOFAR array) is
connected to the A/D channel. If 0 is specified, then the channel is
considered inactive. To compute the number of active channels, simply
count the number of channels with non-zero values for this parameter (11
for the example in the figure). It is not necessary that the active
channels be contiguous as shown in the figure.

Amplifier (AMP). This parameter indicates which of the preamp/pre-whitening
filters (1-20) the hydrophone signal is connected to.

Gain (GN). This parameter indicates the gain step (0-9) manually set on the
final stage of the preamp/pre-whitening filters.
Blocks Per Tape. This parameter will set the number of blocks written to any tape drive before the next tape drive is used. When the value is set to a large number, as shown in the example, the program will write to a drive until the end-of-tape mark is sensed before switching drives. Estimates of how many blocks may fit on a tape can be computed by dividing the block length in bytes by 1600 bytes per inch, adding the length of the preamble, postamble and inter-record gap (~0.6 inches), and dividing into the tape length (28800 inches for a full-reel).

Unit-Drive Serial Number. This information is used to indicate which physical tape drive is connected to the tape drive unit (0-3) recognized by the computer.

Starting Tape Unit Number. This parameter is used to determine which tape drive to write to at the start of program WAKEUP. It is continually updated by WAKEUP to facilitate a smooth recovery after a power failure.

Year and Julian Day - These parameters are necessary because the satellite clock does not output the year. WAKEUP continually reads the Julian day from the parameters file and then updates it with the value output by the satellite clock. When the satellite clock Julian day is less than the Julian day in the parameters file (i.e., at the beginning of a new year), then the year is incremented by one.

Next in the example shown in Fig. 9, the user has typed 8 to display all the commands. No changes were necessary so a 10 was then typed to exit PARAMS.
The values in the parameters file (actually two files, DK:WKPARM.BIN and DK:RCOVERY.BIN) are displayed and control returned to the system.

Current WAKEUP Configuration

The WAKEUP configuration, set up by PARAMS, which has been in operation from 8 September 82 to the present (16 June 83) has the following key features: 1) data is digitized at a rate of 80 samples/sec/channel; 2) there are 8 active channels which are (given in the order in which they are multiplexed) 71, 73, 74, 75, 76, 10, 20, and 40 as previously described in Fig. 4; 3) each block contains 5 seconds of data which produces a block size of 3300 2-byte words (i.e., 3200 words of data plus a 100 word block header) and 4) the number of blocks per tape is large so that tapes are always written to their end-of-tape marks. Although it had been intended to digitize and record 11 hydrophones, which would produce 4 tapes per day, assorted problems with the tape drives have made it necessary to only record 8 hydrophones, which produces 3 tapes per day.

WAKEUP Operator Commands

Because Wake Island is such a remote place, and because those who must operate the system are untrained in computer hardware or software, program WAKEUP has been designed to handle many unusual situations without operator intervention. Only four operator commands are necessary during continuous data collection under WAKEUP, and these are described below:

Switch Drives(S). This command is used to force WAKEUP to write to the next available tape drive. This command is normally executed once per day when the operator comes in to change tapes. First he changes tapes on
those drives which have tapes full of data, and allows WAKEUP to continue writing onto the current drive. When fresh tapes are mounted, he executes the $S$, which causes WAKEUP to start writing to a fresh tape, and then he changes tapes on that last drive. A sample of $S$ is shown in Fig. 5.

Reset($R$). The reset command is nearly identical to the switch drives command, except that WAKEUP will wait for the satellite clock to indicate a change in the minute before it starts the A/D convertor collecting data for the next block. It is desirable to have data blocks which start on an integral second, (or integral minute) because it makes the measurement of time on plots, made later on during data reduction, somewhat simpler. Under ideal conditions, once the block beginnings are synchronized with the minute (i.e., if the number of seconds per block is 5, then all blocks should begin at 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, or 55 seconds after the minute) they should stay that way forever.

Unfortunately, the satellite clock sometimes loses synchronization with the satellite for a while and begins to drift. When resynchronization occurs, the accumulated error gets propagated into the starting times of the blocks. When the operator notices this condition, he can correct it by using reset instead of switch drives. A sample of $R$ is shown in Fig. 5.

Terminate ($T$). This command is used to terminate WAKEUP and return control to the RT-11 operating system.
Display (D). This command is used to display the date, time, and clock status at the beginning of the last data block collected.

Power Fail Recovery

Probably the most harmful abnormal condition, in terms of potential loss of data, from which WAKEUP can recover without operator intervention is a power failure. Temporary periods without power are fairly common on Wake and can be due to storms, construction, and generator problems. Since an operator is only present once per day, an irrecoverable system crash due to a short power failure could cause the loss of the entire day's data. Fortunately, with the help of some unique features in the Datum tape drives (described previously), the DEC LSI-11/2 hardware, and the RT-11 operating system, it was possible to write the WAKEUP program with the capability to resume collecting data after a power failure, without wasting tape (which could cause the system to run out of tape before the operator arrived) and without writing over old data. An essential element of this recovery capability is that the particular tape drive being written to is stored on a disk file. When power comes back after a failure, WAKEUP reads this file and then resumes writing to the proper drive.

WAKEUP Log

All operator input as well as RT-11 and WAKEUP messages and operator prompts go through the printer/console to create a log of events. A sample of this log is shown in Fig. 5, and has already been referred to several times. This log is essential for keeping track of normal system operations as well as problems which occur from time to time. The operator is
responsible for filling in the identification numbers of tapes mounted on each drive.

**WAKEUP Tape Format**

The WAKEUP tapes are numbered sequentially beginning with 10001. A detailed description of the format of the tapes and the blocks contained within the tapes is given in Fig. 10. The date and time given in the header are for the first data point in the block.

**PRELIMINARY DATA REDUCTION SOFTWARE - WAKE HYDROPHONE INFORMATION PROCESSING SYSTEM (WHIPS)**

Because of the large amount of data which is collected by this system (i.e., 50 billion bytes per year or 1500 tapes per year for 11 channels at 80 samples/sec/channel) it was realized that some sort of data compression scheme would have to be implemented in order to efficiently store, manage, retrieve, and distribute those data of current and future interest. These data have been defined in two general categories: 1) seismic phases such as P, S, Po, So, and T, and 2) ambient background noise. Software to sample these categories has been written and its structure is diagramed in the flow chart of Fig. 11. Intervals of data are saved when seismic phases from particular events are suspected of being present; and, in addition, 3-minute intervals of data selected at random times, with an average of one interval per hour, are also saved in order to sample the ambient noise. Three minutes of data is long enough to view several cycles at the longest periods thus far observed on the hydrophones - 20 seconds, and also long enough to provide reasonable statistics on the higher frequencies (1-20 Hz) where most of the oceanic, short-period seismic data are present. By sampling at
**WAKEUP Tape Description**

**General Format:**
- 1600 BPI
- 2 bytes per word
- IBM format
- 2’s complement notation

### All Blocks

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<th>Word(s)</th>
<th>Description</th>
</tr>
</thead>
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<td></td>
</tr>
<tr>
<td>data: words 101-end</td>
<td></td>
</tr>
</tbody>
</table>

| 1       | Year (e.g., 1983) |
| 2       | Julian day (1-366) |
| 3       | Hour |
| 4       | Minute |
| 5       | Second |
| 6       | Millisecond |
| 7       | Digitization rate (samples/sec/channel) |
| 8       | Number of samples/channel/block |
| 9       | Total number of samples/block |
| 10-41   | A/D channel information - 16 channels, 2 words per channel |
|         | 1st word - hydrophone I.D. number |
|         | (0 if channel not used) |
|         | 2nd word - hundreds and tens digit is the amplifier I.D. number, units digit is the amplifier gain step |
| 42      | Tape unit (0-3) |
| 43      | Tape drive serial number |
| 44      | Clock status |
| 45      | A/D buffer size |
| 46-100  | Not used |
| 101-end | Digitized hydrophone data (multiplexed-order of hydrophones is the same as the order of the active channels described in words 10-41) |

---

Figure 10. The WAKEUP tape format.
Figure 11. Generalized flow chart of the programs and files used in the preliminary reduction of the Wake digital data.
random time intervals, periodic noise of artificial nature is hopefully avoided. This system of programs and files which performs processing of the WAKEUP data is called WHIPS for Wake Hydrophone Information Processing System, and is run on a Harris model H800 computer.

**WAKEUP Log Entry (XTAPE)**

An initial step in the WHIPS procedure is to create or update file TAPLOG, which contains an identification number, starting time, block count, and status of each tape created by WAKEUP. This information is entered from the WAKEUP log (Fig. 5), using interactive program XTAPE. The data is necessary, as input to program STRIP, for calculating the time window to be processed for the compression of a given range of WAKEUP tape. Some sample data contained in TAPLOG, and printed out using program XTPLST is shown in Fig. 12. The total time represented on an individual tape can be found by multiplying the number of blocks by the number of seconds per block (which is 5 seconds per block for the tapes shown). The tape status indicates whether the tape is available for current or further processing (ACTIVE), or has been recycled (RECYCL).

**Event Data Entry (XEVENT)**

Another initial step in the WHIPS procedure is to create or update file EVENTS, which contains data about each earthquake for which an interval of data is to be saved. A sample of data contained in this file has been listed using program XEVLST and is shown in Fig. 13. Hypocenter/origin-time data are taken mostly from the Preliminary Determination of Epicenter (PDE) lists, published by the National Earthquake Information Service (NEIS), although other sources of data are used to complement the PDE's when
**Figure 12.** A sample of the WAKEUP tape information contained within WHIPS file TAPLOG which has been printed using program XTPLST. A detailed description of this printout is contained in the text.
### MAKE HYDROPHONE INFORMATION PROCESSING SYSTEM (WHIPS) EVENT LISTING

**27 JUN 83**

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<th>SAVC</th>
<th>TAP/F</th>
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<td>ARD</td>
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<td>ARD</td>
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</table>

**Figure 13.** A sample of event information contained within WHIPS file EVENTS, which has been printed using program XEVLIST. A detailed description of this printout is contained in the text.
necessary. A general procedure has been formulated for determining which events from the PDE lists might produce seismic energy observable at Wake, based on experience gained from scanning the analog data collected since 1979. An outline of event types and their corresponding phases is presented in Fig. 14. Intervals to save for these events and phases are computed automatically by program XEVENT, at the time the hypocenter data are entered, and may be altered manually if necessary. The only seismic energy from events which is deliberately discarded is that of T-phases from smaller magnitude and unknown events. T-phase energy is generally so abundant (it is estimated that at least 10 times as many circum-Pacific events may be detected using T-phases than may be detected using other seismic phases) that very little data compression would be possible if all of these T-phase data were saved. This procedure is weighted towards saving more data than necessary (i.e., many of these events may not have observable energy at Wake, but this is hard to determine without scanning all the channels in particular frequency bands) so that a) unusual events are not discarded, b) data from small events may be enhanced with array processing, and c) data from events which are not of current interest but may be of future interest are saved. The helicorder records from Wake are also scanned for seismic phases such as P, Po, S, and So which do not correspond to known events, and intervals are saved to capture these phases. Two such intervals, corresponding to events 820 and 826, appear in Fig. 13. The final column of the listing shown in Fig. 13 gives the strip tape and file number which contains the corresponding interval of data. Some data intervals are contiguous or overlap and have therefore been saved in a single file (for example: events 807 and 808, and events 813 and 814). Other events have not yet been extracted from the WAKEUP tapes and are noted
<table>
<thead>
<tr>
<th>Source Region(s)</th>
<th>Magnitude</th>
<th>Depth(km)</th>
<th>$\sim \Delta$</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Nuclear Explosions Anywhere</td>
<td>all</td>
<td>all</td>
<td>$0^\circ-35^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td></td>
<td>all</td>
<td>all</td>
<td>&gt; $35^\circ$</td>
<td>P</td>
</tr>
<tr>
<td>2. Mariana Is., Bonin Is., Volcano Is., Honshu, and Gilbert Islands</td>
<td>$m_b &lt; 5.0$</td>
<td>&lt;100</td>
<td>$18^\circ-25^\circ$</td>
<td>P,Po.So.</td>
</tr>
<tr>
<td></td>
<td>$m_b &gt; 5.0$</td>
<td>&lt;100</td>
<td>$18^\circ-25^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td></td>
<td>all</td>
<td>&gt;100</td>
<td>$18^\circ-25^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td>3. Kuril Is., Kamchatka, Aleutian Is., New Guinea, New Britain, Solomon Is., and Santa Cruz Islands</td>
<td>$m_b &gt; 5.0$</td>
<td>&lt;100</td>
<td>$25^\circ-35^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td></td>
<td>all</td>
<td>&gt;100</td>
<td>$25^\circ-35^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td>4. Asian Continent</td>
<td>$m_b &gt; 4.5$</td>
<td>all</td>
<td>$30^\circ-90^\circ$</td>
<td>P</td>
</tr>
<tr>
<td>5. Mid Pacific Plate Events</td>
<td>all</td>
<td>all</td>
<td>$0^\circ-35^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td></td>
<td>$m_b &gt; 4.5$</td>
<td>all</td>
<td>&gt;$35^\circ$</td>
<td>P,Po.So.T</td>
</tr>
<tr>
<td>6. Not Regions 2, 3, 4, or 5.</td>
<td>$m_b &gt; 5.0$</td>
<td>all</td>
<td>&lt;$90^\circ$</td>
<td>P</td>
</tr>
<tr>
<td>7. Mid Atlantic Antipode</td>
<td>all</td>
<td>all</td>
<td>$340^\circ-360^\circ$</td>
<td>P</td>
</tr>
<tr>
<td>8. Anywhere</td>
<td>$M &gt; 6.0$</td>
<td>all</td>
<td>all</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>$m_b &gt; 6.5$</td>
<td>all</td>
<td>$340^\circ-360^\circ$</td>
<td>P</td>
</tr>
</tbody>
</table>

Figure 14. The general criteria used for deciding which phases (if any) to save for a known event. Time intervals which contain those phases are computed automatically by XEVENT or may be entered manually.
by a tape and file number of 0 (such as event 850). Some events, such as
801, 806, and 811, could not be extracted because there was no WAKEUP data
available (in this case, due to a tape drive failure at WAKE). A file for
these events, containing only header and trailer records, exists on the
strip tape indicated, and the file number has been flagged as negative on
the XEVLST listing.

**XSTRIP Parameters (XPARAM)**

The last initial step in the WHIPS procedure is to set up the running
parameters for program XSTRIP which are stored in the header block of the
EVENTS file. These parameters may be viewed and changed using program
XPARAM, and a sample output from this program is shown in Fig. 15. Many of
these parameters (D, E, F, G, H, and I) are continually updated by programs
XSTRIP, XSTPDN, and XRANDN; and these parameters may be changed manually
when necessary. Other parameters (A, B, and C) must always be entered and
changed manually as the situation warrants. The "WAKEUP tape record length"
(A) is equal to the WAKEUP sampling rate times the number of channels, times
the number of seconds per block, plus 100 words for the block header (i.e.,
\[80 \times 8 \times 5] + 100 = 3300\). The "strip/interval disk record length" (A) is
the block length used for disk files STRIP000 and INTRVLOO; and it must be a
multiple of 112 words (Harris sector size = 112 words) which is greater than
or equal to the WAKEUP tape record length. The "maximum records ..." (B) is
a conservative estimate of how many blocks of data (in this case, 3300 word
blocks) will fit onto a tape created by XSTPDN or XRANDN. This parameter
is necessary for XSTPDN to organize its output data so that individual
intervals which are saved do not cross XSTPDN tape boundaries. The "seconds
per WAKEUP tape block" (C) is used to convert terms which refer to a
WHIPS-->DEFINE SYSTEM PARAMETERS.

A. WAKEUP TAPE RECORD LENGTH IS 3355
   STRIP/INTERVAL DISC RECORD LENGTH IS 3360
B. MAXIMUM RECORDS ON EVENT/INTERVAL TAPE IS 5588
C. SECONDS PER WAKEUP TAPE BLOCK IS 5
D. NEXT WAKEUP TAPE TO STRIP IS 18500
   LAST WAKEUP TAPE TO STRIP IS 5
E. LAST RECORD ON STRIP DISC FILE IS 5
F. CURRENT STRIP TAPE NUMBER IS 25544
   LAST FILE WRITTEN IS 5
   NUMBER OF TAPE RECORDS IS 1222
G. LAST RECORD ON INTERVAL DISC FILE IS 5
H. CURRENT INTERVAL TAPE NUMBER IS 3829
   NUMBER OF TAPE RECORDS IS 3056
I. RANDOM INTERVAL 2626668179995

ENTER A-J, U (UPDATE), OR X (EXIT).

Figure 19. A part of the interactive I/O generated by WHIPS program XPARAN which is used to view or change the running parameters of program XSTRIP. More detailed explanation of these parameters is given in the text.
particular block on a WAKEUP tape into absolute times (for example – to calculated the ending time of a WAKEUP tape, given its starting time and total number of blocks). The "next" and "last WAKEUP tape to strip" (D) refers to the range of WAKEUP tapes which are to be processed during a particular run of XSTRIP. These parameters are continually updated during the XSTRIP run to facilitate recovery in case of a system crash. At the completion of the run, the last tape which was processed becomes the "next WAKEUP tape to strip", and the "last WAKEUP tape to strip" is set to 0, as shown in the figure. The "last record on the strip disk file" (E) allows XSTRIP to begin writing into STRIP000 where it last left off. This parameter is set to 0 after a successful downloading of the data using XSTPDN, as is shown in the figure. The "current strip tape", "last file", and "number of tape records" (F), allows XSTPDN to download the data onto tape from the point on the tape at which it left off after the last run. G and H serve the same function for the random interval data as did E and F for the stripped events data. The "random interval" (I) gives the 3 minute time range, in century-milliseconds, of the next random interval to be stripped.

Extracting the data (XSTRIP)

XSTRIP is the program which extracts and stores data of events and of random intervals on disk for later downloading. The only operator input required is specification of the range of WAKEUP tapes to be processed. Normally, this processing takes place in contiguous chronological order. After the total time interval represented by the WAKEUP tapes has been computed from the TAPLOG file, a search of the EVENTS file is made to determine which event intervals, not yet extracted, lie entirely within the
total time interval. From these individual event intervals, grand intervals are computed which combine the times of overlapping event intervals. As the WAKEUP tapes are read one by one (the operator is prompted to mount each tape), the grand intervals are extracted and stored on disk file STRIPO00. Concurrently, the random, three-minute intervals are being extracted and stored on disk file INTRVLO0. The timing of these intervals is computed "on the fly" and the number of minutes of data between the beginnings of one 3-minute interval and the next is computed using a random variable with a uniform distribution between 3 (i.e., no overlap) and 117, giving an average separation of 60 minutes. The parameters list at the beginning of the EVENTS file is updated after the extraction of each grand interval and each random interval. This facilitates a smooth and efficient recovery after an XSTRIP abortion of any kind and provides information for later downloading of the data to tape. XSTRIP is complete after the last WAKEUP tape has been run. It should be noted that a typical XSTRIP run at HIG processes from 10 to 20 WAKEUP tapes, and requires approximately 20 million words of disk storage for the STRIPO00 and INTRVLO0 files.

Events Download to Strip Tapes (XSTPDN)

The STRIPO00 disk file containing the event data is downloaded to tape using program XSTPDN. This program first accesses the running parameters in the EVENT file to find out which tape to download to, and how many files to advance into that tape before writing. As each grand interval in the STRIPO00 file is downloaded to tape, the running parameters are updated, and the EVENTS file is updated with the strip tape number and file for those events contained in the grand interval. If the grand interval contains too many records to completely fit on the strip tape (based on "B" in the
running parameters), then an end-of-file is written to the strip tape and a new strip tape is mounted following a prompt to the operator. Strip tapes are numbered sequentially beginning with 20001. The XSTPDN run is complete when all the grand intervals have been downloaded, and at that time the "last record on strip disk file" (E) in the running parameters is set to 0 as shown in Fig. 15. The format of the strip tape, and format of the blocks contained on the strip tape is given in Fig. 16.

Random Interval Download to Interval Tapes (XRANDN)

The INTRVLOO disk file, containing the 3-minute randomly spaced ambient noise samples, is downloaded to tape using program XRANDN. This program first accesses the running parameters to determine which interval tape to download to, and how many records from the INTRVLOO file to tape until the maximum number of records on tape ("B" in the running parameters) is reached. There are no end-of-files between the 3-minute intervals, however, an end-of-file is written after the last record on the interval tape. Interval tapes are numbered sequentially beginning with 30001. The XRANDN run is complete when all of the records in INTRVLOO have been downloaded, at which time item "C" in the running parameters is set to 0 as shown in Fig. 15. The format of the interval tape, and the format of the blocks contained on the interval tape is given in Fig. 17.

Checking Procedures (XSTPCHK and XINTCHK)

As a safety measure, and as a way of accumulating some preliminary statistics on the data, all strip and interval tapes are checked using programs XSTPCHK and XINTCHK, respectively. The outputs from these programs are viewed before the STRIPO00 and INTRVLO0 files are eliminated from disk.
The format of the strip tape data blocks is exactly the same as the format of the WAKEUP tape blocks.

Figure 16. Format for the WHIPS strip tapes which contain the event data.
WHIPS Interval Tape Description

General Format: 1600 BPI
2 bytes per word
IBM format
2's complement notation

<table>
<thead>
<tr>
<th>Tape Header Block</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word(s)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Always 0 to identify block as a tape header</td>
</tr>
<tr>
<td>2</td>
<td>Interval tape I.D. number</td>
</tr>
<tr>
<td>3-end</td>
<td>Not used</td>
</tr>
</tbody>
</table>

Note: tape header block is the same size as the data block

<table>
<thead>
<tr>
<th>Data Block</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The format of the interval tape data blocks is exactly the same as the format of the WAKEUP tape blocks.</td>
</tr>
</tbody>
</table>

Figure 17. Format for the WHIPS interval tapes which contain randomly spaced 3-minute intervals of data (1 per hour on the average) which are collected as noise samples.
and the WAKEUP tapes recycled. A sample output from XSTPCHK is shown in Fig. 18. Most of the lines of output are self-explanatory. The "error blocks" are for blocks of data which had tape read errors coming off of the WAKEUP tapes during XSTRIP. The "clipped data" lines show the number of data points in a particular block, and for a particular channel, which are equal to -32,768 or 32,767, the maximum and minimum values output by the A/D convertor at Wake. The clipped data in this file is on two SOFAR hydrophones and corresponds to the T-phase arrival from event 824 (see Fig. 11 for event 824). The table of values gives information about each multiplexed in the file which is described as follows: 1) "ch" - multiplexed channel number; 2) "hydr" - hydrophone number; 3) "amp" - preamp/pre-whitening filter identification number; 4) "gain" - gain step of the final stage of the preamp/pre-whitening filter (see previous section on the recording system); 5) "avgval" - the average value of this channel (non-zero due to small but constant DC biases in the amplifiers); 6) "stddev" - the standard deviation of each channel (note the much higher values for the noisier SOFAR hydrophones); 7) "O/blk" - average number of zeros per block (note that channel 3 has most zeros due to its near zero average value and small standard deviation); 8) "O/blk/std" - the standard deviation of the number of zeros per block; and 9) "# clips" - the total number of clipped data points for this channel in this file. The "worst case clock error code" indicates the maximum error between the satellite clock time written in each block header and the actual coordinated Universal Time. The codes are as follows:

0 - less than + 1 msec
1 - less than + 5 msec
**Figure 18.** Sample output from program XSTPCHK. Detailed explanation of this figure is given in the text.
3 - less than ± 50 msec
7 - less than ± 500 msec
15 - more than ± 500 msec

A sample output from XINTCHK is shown in Fig. 19. Much less computation is
done on the interval data, and the XINTCHK output serves more as a simple
log of what has been saved.

**Strip Tape Copies (XTAPCOP)**

As a final step in the preliminary processing, the strip tapes are
copied using program XTAPCOP, and the copies are sent to the DARPA Center
for Seismic Studies (CSS) in Rosslyn, Virginia. Copies of interval tapes
are not currently sent to CSS but may be at some time in the future.
Figure 19. Sample output from program XINTCHK showing some of the 3-minute intervals saved on a WHIPS interval tape. The first interval shown, blocks 2-22, contains only 105 seconds because part of that interval was written to the previous interval tape. Another interval, blocks 1247-1318, contains 360 seconds and represents two contiguous 3-minute intervals.
ACKNOWLEDGEMENTS

This system has been sponsored primarily by the Air Force Office of Scientific Research with supplemental funds provided by the U.S. Arms Control and Disarmament Agency. Appreciation is expressed to Dan Walker, George Sutton, Paul Jubinski, Grant Blackinton and Joe Gettrust for their respective contributions towards the design and implementation of this system. Firmin Oliveira successfully programmed most of the WAKEUP and WHIPS software in less time than seemed possible. Al David, Bonnie Jose, and Kentron Corporation have provided excellent day to day operation of the system at Wake.
APPENDIX X
<table>
<thead>
<tr>
<th>Event</th>
<th>Origin Time</th>
<th>Coordinates</th>
<th>Location</th>
<th>DEF</th>
<th>MAGN</th>
<th>INT</th>
<th>Event Time</th>
<th>Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17:27:39.8</td>
<td>37.2874</td>
<td>73.7845</td>
<td>TAIJIK-SINJANG BORDER REGION.</td>
<td>32.4</td>
<td>4.6</td>
<td>PDE A</td>
<td>12:45-12:56</td>
</tr>
<tr>
<td>2</td>
<td>17:30:18.5</td>
<td>37.2874</td>
<td>73.7845</td>
<td>TAIJIK-SINJANG BORDER REGION.</td>
<td>32.4</td>
<td>4.6</td>
<td>PDE A</td>
<td>12:45-12:56</td>
</tr>
<tr>
<td>3</td>
<td>17:40:28.4</td>
<td>37.2874</td>
<td>73.7845</td>
<td>TAIJIK-SINJANG BORDER REGION.</td>
<td>32.4</td>
<td>4.6</td>
<td>PDE A</td>
<td>12:45-12:56</td>
</tr>
<tr>
<td>4</td>
<td>17:46:28.4</td>
<td>37.2874</td>
<td>73.7845</td>
<td>TAIJIK-SINJANG BORDER REGION.</td>
<td>32.4</td>
<td>4.6</td>
<td>PDE A</td>
<td>12:45-12:56</td>
</tr>
</tbody>
</table>

**KEY:**
- **EVENT:** Earthquake, E=NUCLEAR EXPLOSION, S=OTHER, UN=UNKNOWN
- **DEF:** A=W=UEBC, B=PO, C=SS, D=SO, E=OTHER

**PHASES:**
- **A:** For PDE, B=PO, C=SS, D=SO, E=OTHER
- **M:** Magnitude
- **S:** Source
- **F:** PHASE
- **I:** INTERVAL
- **MS:** Time
- **T:** Taper

**NOTE:**
- **NO:** NO MAGNITUDE
- **NO:** NO EVENT
- **NO:** NO PHASES
- **NO:** NO INTERVAL
- **NO:** NO TAPER

**EVENT TIMING:**
- **ORIGIN:** The origin time of the event.
- **COORDINATES:** The geographical coordinates of the event.
- **LOCATION:** The region where the event occurred.
- **DEF:** The definition of the event.
- **MAGN:** The magnitude of the event.
- **INT:** The interval of the event.
- **Event Time:** The time at which the event occurred.
- **Saved:** Whether the event was saved or not.

**PHASES:**
- **A:** For PDE, B=PO, C=SS, D=SO, E=OTHER
- **M:** Magnitude
- **S:** Source
- **F:** PHASE
- **I:** INTERVAL
- **MS:** Time
- **T:** Taper

**NOTE:**
- **NO:** NO MAGNITUDE
- **NO:** NO EVENT
- **NO:** NO PHASES
- **NO:** NO INTERVAL
- **NO:** NO TAPER

**ORIGIN:**
- **ORIGIN:** The origin time of the event.
- **COORDINATES:** The geographical coordinates of the event.
- **LOCATION:** The region where the event occurred.
- **DEF:** The definition of the event.
- **MAGN:** The magnitude of the event.
- **INT:** The interval of the event.
- **Event Time:** The time at which the event occurred.
- **Saved:** Whether the event was saved or not.
null
<table>
<thead>
<tr>
<th>EVENT</th>
<th>EVENT DESCRIPTION</th>
<th>LOCATION</th>
<th>DEP</th>
<th>IMF</th>
<th>SAVED</th>
</tr>
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<td>2A8</td>
<td>EQ ABE</td>
<td>2.9</td>
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<td>2.6</td>
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<tr>
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<tr>
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<td>2.6</td>
<td>2.2</td>
<td></td>
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<tr>
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<td>2.6</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
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<td>2.2</td>
<td></td>
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<td>2.6</td>
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<td></td>
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<td>2.2</td>
<td></td>
</tr>
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**MAKE HYDROPHONE INFORMATION PROCESSING SYSTEM (WHIPS) EVENT LISTING**

**KEY: INFORMATION SOURCES - PDE=NEIS PCARD, HOM=NEIS MONTHLY LIST, ICS=ICS LIST, HEL=HELICORDER, OTH=OTHER.**

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**PHASES - A=AP, B=BO, C=CS, D=SO, E=T-OTHER.**

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