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ENVIRONMENTAL ASPECTS OF A NORTH PACIFIC ACOUSTIC FIXED-SOURCE,--ETC(U)
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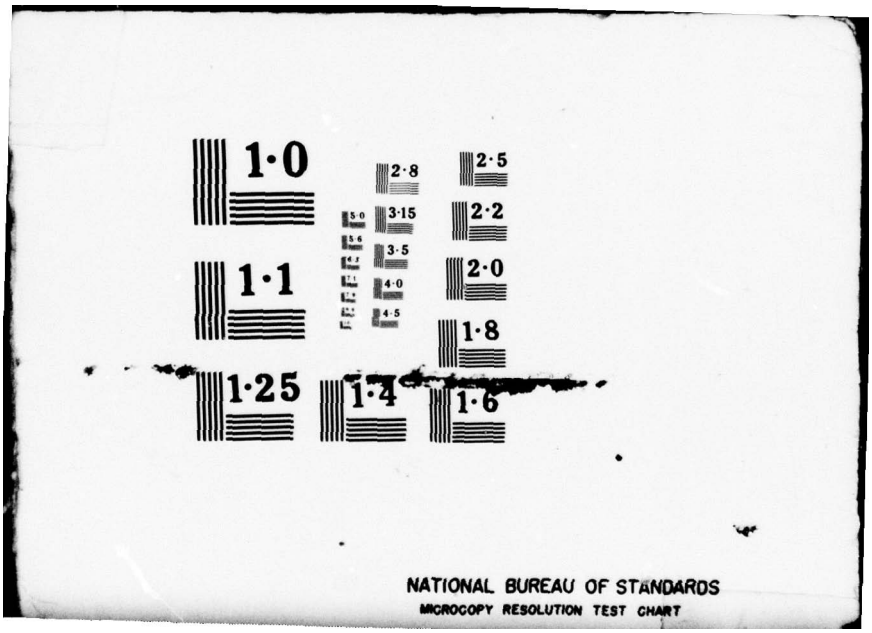
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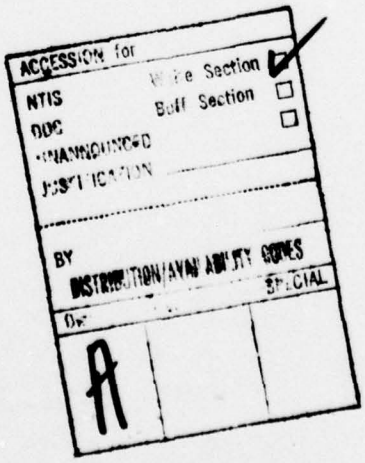
ENVIRONMENTAL ASPECTS OF A NORTH PACIFIC ACOUSTIC FIXED-SOURCE, FIXED-RECEIVER INSTALLATION

by M. Schulkin

A TECHNICAL REPORT FOR THE PERIOD 1 MARCH 1977 TO 1 MARCH 1979
CONTRACT N00014-77-C-0309 (MOD P00002)

APL-UW 7905
1 March 1979



ACKNOWLEDGMENTS

In carrying out this program covering so many facets of oceanography and underwater acoustics, the author has had the benefit of many generous sources of information, advice, and assistance. The author appreciates these considerations and has attempted to acknowledge such sources in the text and references. However, there are a few individuals whose contributions have been clearly dominant. These I acknowledge with pleasure as: Dr. D.R. McLain (NMFS, NOAA), Dr. T.M. Davis (NAVOCEANO), Mrs. Rosa T. Washington (NODC), Dr. E.W. Schwiderski (NSWC), Mr. R. Van Wyckhouse (NORDA), and Dr. A.O. Sykes (ONR).

ABSTRACT

The Office of Naval Research (Code 222) is sponsoring an experimental program in the Northeast Pacific Ocean to investigate long-term variations in propagation loss and travel time between a fixed source and fixed receiver over extremely long paths. This report considers environmental factors which are expected to be important for acoustic modeling and prediction, particular attention being given to mesoscale features, or "ocean weather." Existing and planned environmental data sources and formats are reviewed in terms of the requirements. Cost-effectiveness is emphasized. Monthly weeklong shallow XBT (480 m) sampling of the 3835-km Oahu to San Francisco path by the National Marine Fisheries Service (NOAA) ship-of-opportunity program is found to serve well as a basis. However, the sampling depth must be increased beyond the sound channel axis at about 800 m, and the spacing of drops should be reduced to about 30 km in the vicinity of sharp temperature and salinity gradients. A program has been implemented to merge the taped historical oceanographic station data file (NAVOCEANO) with synoptic XBT and salinity data (NMFS). Available bathymetric (NORDA) and M_2 tidal (NSWC) data banks appear to be quite satisfactory. It is highly desirable to obtain long-term time-series temperature variability data down to depths below the sound channel axis using thermistor arrays at a suitable location along the path. The use of satellites and remote sensing aircraft to supplement the existing data acquisition programs is strongly recommended. Existing computer models of extremely long-range acoustic transmission loss verify relatively large measured range-dependent effects upon crossing fronts, currents, and eddies. The results of previous long-term time-series measurements of propagation loss for the 1250-km Eleuthera-Bermuda fixed path at 406 Hz are presented as a reference.

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I. INTRODUCTION

The Office of Naval Research (Code 222) is sponsoring an experimental program in the Northeast Pacific Ocean to investigate long-term variations in propagation loss and travel time between a fixed source and fixed receiver over extremely long paths. Particular attention is given to a fixed acoustic path between Oahu, Hawaii, and San Francisco (3835 km). The purpose of this ONR study is to determine the relationship of these variations to large space-time scale ocean processes. The acoustic data should also be useful for the study of fluctuations and variations resulting from other ocean effects, e.g., internal waves, tides, finestructure, surface waves and currents, current gradients, and the presence of bottom topography.

This report considers the environmental factors that are expected to be significant for studying long-term acoustic variability. The purpose of the present work is to recommend a cost-effective environmental data acquisition program taking into account the most significant ocean variables that can be applied to acoustic modeling in support of the ONR fixed-source fixed-receiver propagation measurements. The focus of the work has been to uncover existing data sources and data banks and to examine the adequacy of existing measurement and analysis capabilities which could be applied to the problem. The first stage has been planned and is being implemented by ONR in collaboration with the National Marine Fisheries Service (NMFS, NOAA), the Naval Oceanographic Office (NAVOCEANO), and the Fleet Numerical Weather Central (FNWC). Work is continuing on expanding the Northeast Pacific areal coverage, and on relating mesoscale surface features to features at depth.

Statistical, spectral, dynamic structural, and historical data methods are being applied to the problem of describing and forecasting "ocean weather" for the present acoustical purpose. The term "ocean weather" is appropriate because the time and length scales that are associated with the warm and cold mesoscale ocean features are reminiscent of cyclones and anticyclones observed in atmospheric weather systems. The material on water masses, fronts, currents, tides, bottom topography, and sound speed provinces summarizes data and data systems presently available, albeit difficult to obtain. Next covered are programs in progress involving sampling of the internal temperature, density and sound speed field, dynamic height, currents, and wave heights related to instrumentation and observational platforms such as ships, buoys, aircraft and satellites. Finally, presently available experimental acoustic data over long-range paths in other parts of the world oceans are introduced, along with performance estimates provided by existing acoustic models for fixed and moving sources, narrow and broad band.

II. NORTH PACIFIC OCEAN WATER MASSES, FRONTS AND CURRENTS

II-1. Schematic Map of Main North Pacific Fronts

First let us review the oceanographic features of the North Pacific Ocean and how these relate to the problem of monitoring the environment of an acoustic path between Oahu and San Francisco. We are particularly interested in the time and length scales of these environmental features.

Figure II-1 shows the basic frontal, water mass, and water current regions of the North Pacific. The region between the Subtropical Front and the Subarctic Front is called the Transition Zone. The acoustic path starts at Oahu in subtropical water, known as Eastern North Pacific Central Water, crosses the Subtropical Front near the position of Ocean Weather Ship (OWS) NOVEMBER at about the halfway point (30°N, 140°W), passes through a section of the Transition Zone, enters the California Current region, and ends in the coastal zone of San Francisco.

Table II-1 provides a comparison of the horizontal acoustic and oceanographic properties of the main North Pacific frontal and current zones.

Table II-1. Characteristics of North Pacific fronts, based on horizontal sampling at 30 km intervals. All gradients are expressed in terms of the Nyquist sampling interval. (from Ref. II-1; reproduced with permission)

	North Pacific Fronts				
Characteristics*	Kuroshio	Oyashio	Subarctic	Subtropical	Doldrum
Temperature gradient (°C per 60 km)	6	9	8	4	1
Salinity gradient (‰ per 60 km)	0.6	1.5	1.2	0.5	1.0
Sound velocity gradient ($m\ s^{-1}$ per 60 km)	24	39	28	12	1
Density gradient ($kg\ m^{-3}$ per 60 km)	0.8	0.2	0.2	0.8	0.7
Baroclinic current ($m\ s^{-1}$)	0.6	0.2	0.4	0.5	0.5
Baroclinic shear (s^{-1})	2×10^{-5}	8×10^{-6}	7×10^{-6}	10^{-5}	2×10^{-5}

*Maximum values

Figure II-2 is taken from The Oceans, by Sverdrup, Johnson and Fleming, and shows the distribution of water masses as identified by their T-S curves. We see that the acoustic path goes through Eastern North Pacific Central Water, the Transition Region, and the California Current.

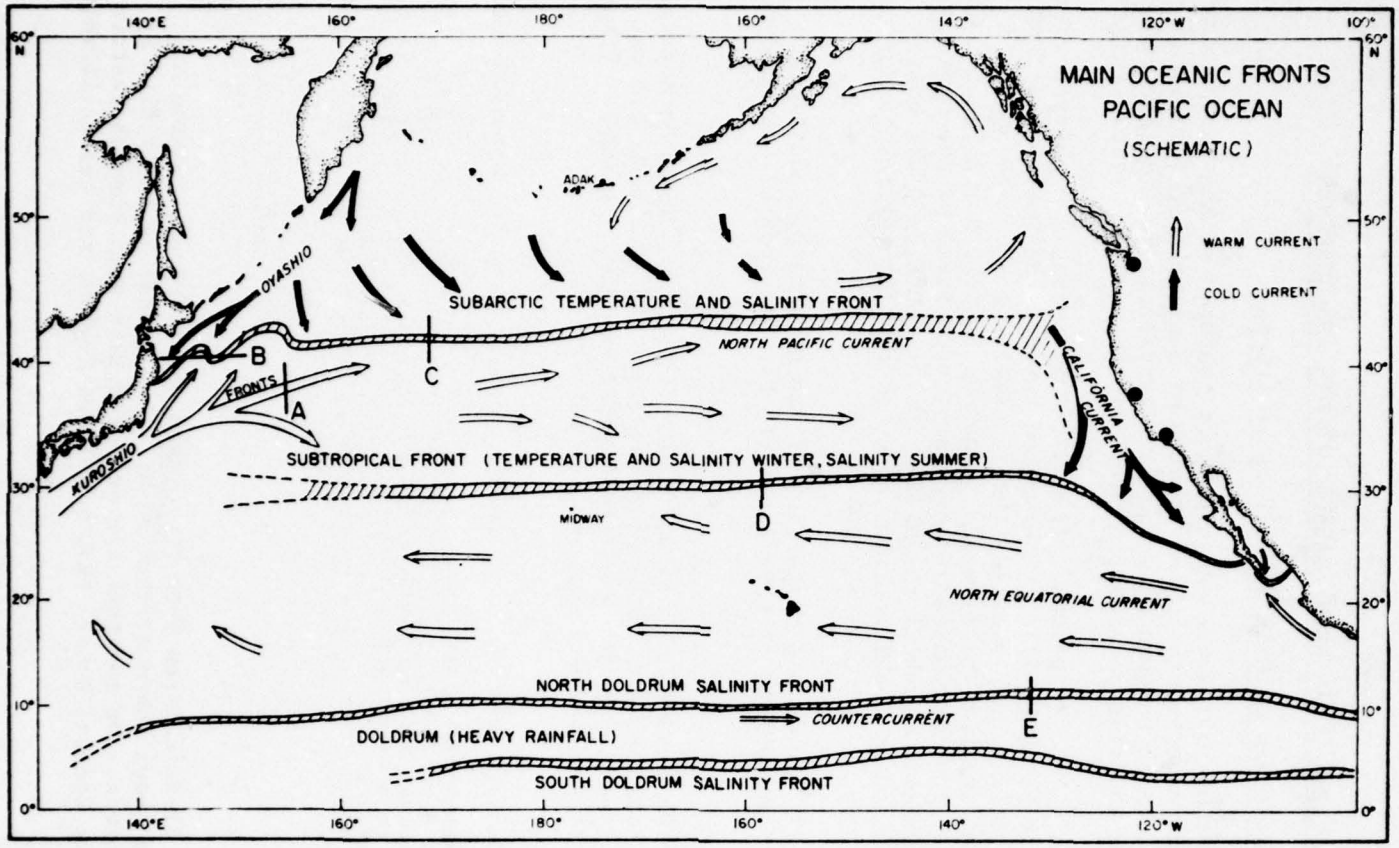

Figure II-1. Schematic map of main North Pacific fronts. Arrows indicate prevailing current directions. Letters refer to fronts: A, Kuroshio front; B, Oyashio front; C, subarctic front; D, subtropical front; E, doldrum front. (from Ref. II-1; reproduced with permission)

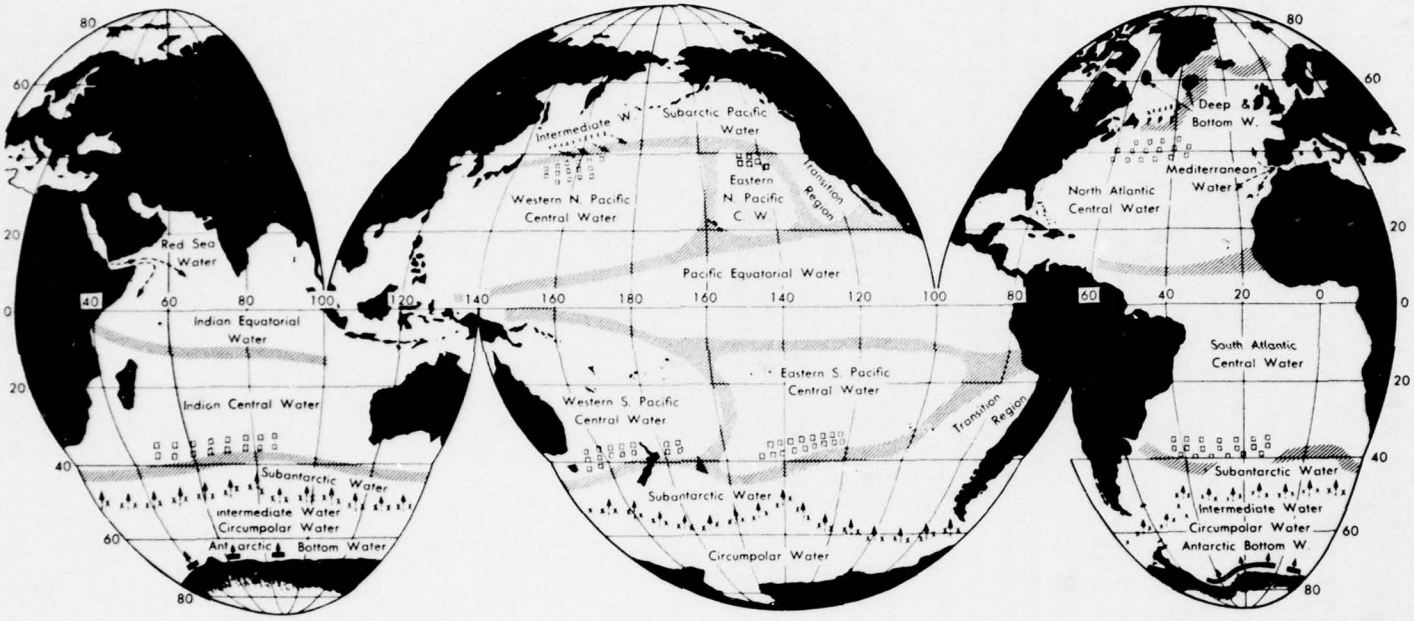

Figure II-2. The geographic distribution of water masses that have common vertical salinity and temperature distributions, as denoted by their T-S curves. (from Ref. II-2; reproduced with permission)

II-2. Fixed Acoustic Path Traverses Ocean Sub-Gyre

An important property of the Oahu to San Francisco acoustic path can be seen in Figure II-3. For the most part, the path passes through an oceanic sub-gyre formed by the splitting of the primary clockwise circulation pattern: easterly trade winds, Kuroshio, westerlies, California current, and into two wind-driven gyres. The split occurs just to the west of the Hawaiian Islands. The boundary of the gyre migrates somewhat over the year, and from year to year, depending on the position of the atmospheric semipermanent high pressure region that overlies the Eastern North Pacific.

NAVOCEANO SP 1402-NP8, "Surface Currents--North Central North Pacific Ocean" (Ref. II-4), and others in the same series provide a summary of historical surface current vectors by month for 1° x 1° squares. Such data may be useful for studying the effects of water motion and circulation on acoustic propagation.

Figure II-4 shows the transection of three radials from Oahu to Los Angeles, San Francisco and Seattle through the same water mass regions. The radial to San Francisco seems to be a turning locus for the east-west section of the Transition Zone to a more north-south orientation. The observations were taken as part of the ship-of-opportunity XBT measurement program of the National Marine Fisheries Service (NOAA).

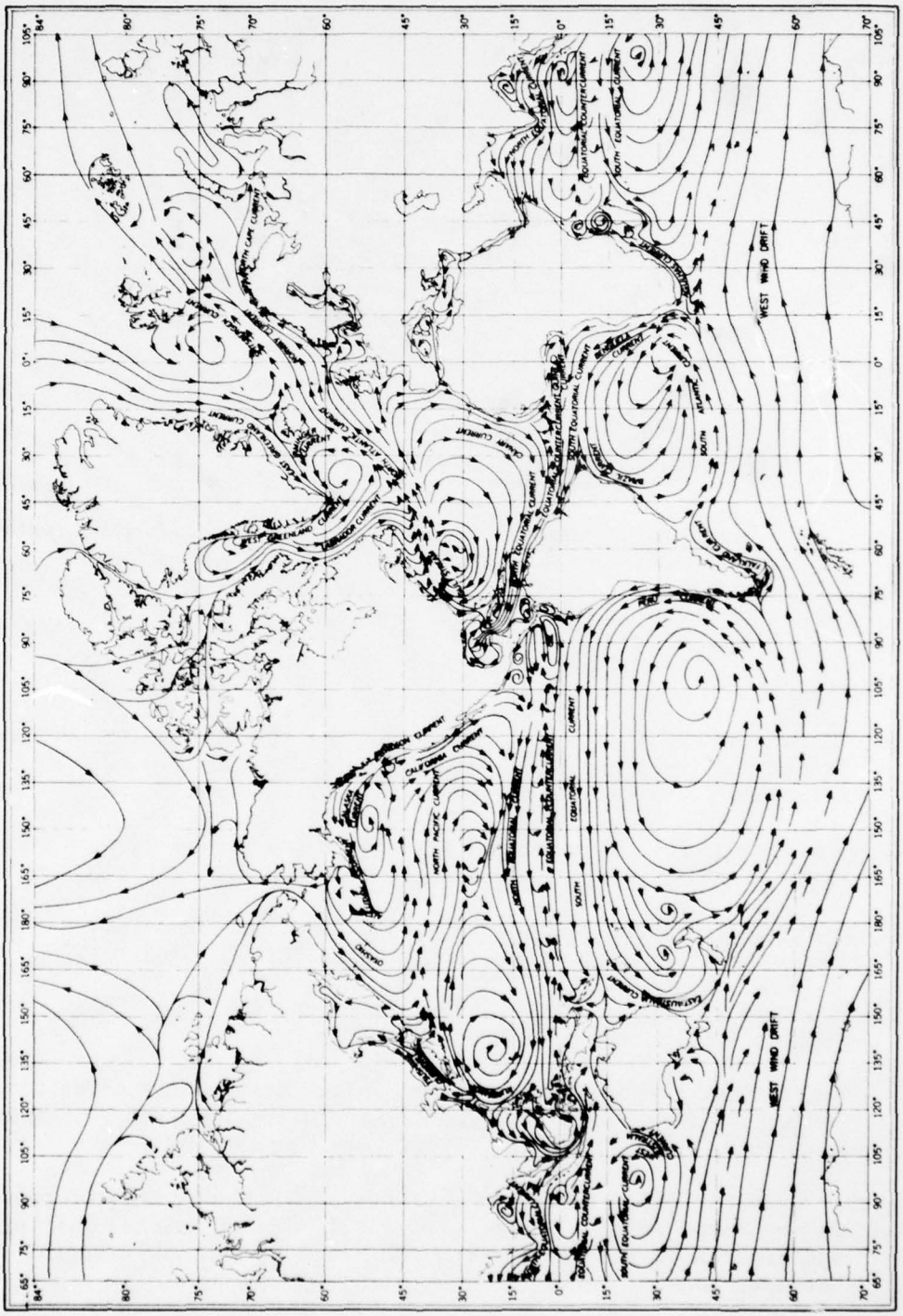

Figure II-3. Major surface currents of the world; winter in Northern Hemisphere. (from Ref. II-3)

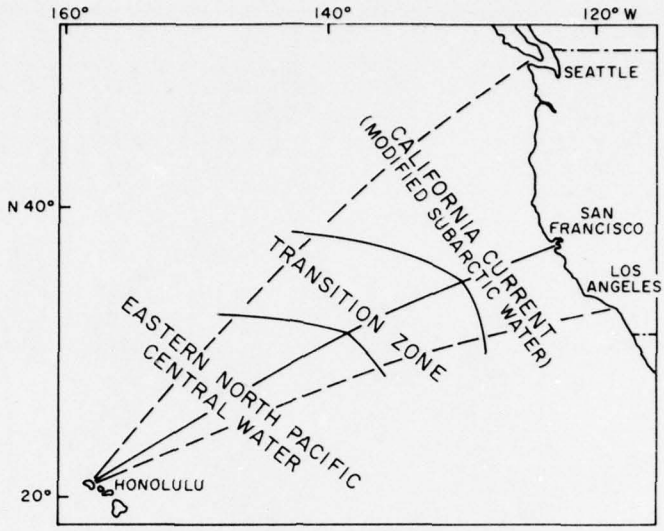

Figure II-4. Sections of expendable bathythermograph observations were taken on, or near, the great circle route between Oahu and San Francisco. The surface water masses in the region are shown schematically. (from Ref. II-5)

II-3. References

II-1. "On North Pacific temperature, salinity, sound velocity and density fronts and their relation to the wind and energy flux fields," G.I. Roden, J. Phys. Oceanogr. 5, 557-571 (1975).

II-2. The Oceans, H.U. Sverdrup, M.W. Johnson and R.H. Fleming (Prentice-Hall, Inc., New York, fourth printing, 1952) p. 740.

II-3. American Practical Navigator, N. Bowditch, H.O. Pub. No. 9 (Government Printing Office, Washington, D.C., 1966) p. 720.

II-4. "Surface currents--North Central Pacific Ocean," NAVOCEANO Special Publication 1402-NP8, July 1977.

II-5. "Subsurface temperature structure in the Northeast Pacific Ocean," in Fishing Information, 8, (NOAA, Nat. Mar. Fish. Serv., Southwest Fisheries Center, La Jolla, California, August 1974).

General: Dr. G.I. Roden furnished reprints of his comprehensive papers on the North Pacific Ocean. Dr. J.F.T. Saur furnished listings and reports of his studies for the National Marine Fisheries Service, NOAA.

III. TIDES OF THE NORTHEAST PACIFIC

III-1. Introduction

Tidal effects are very important for the fixed acoustic path: They stretch or constrict vertical ocean cross sections, cause the propagation of internal waves, and cause currents to flow in response to their forces. Figure III-1 shows semidiurnal, or M_2, cotidal lines of the world ocean as drawn in 1904. This is the most important tidal component. The cotidal lines are lines of constant tidal phase. The points from which they radiate are called amphidromic points or amphidromes. As the earth turns, the cotidal lines appear to rotate about the amphidromes.

III-2. Schwiderski Model for M_2 Tide

The most complete predictive study of global ocean tides has been given by Dr. E.W. Schwiderski (Ref. III-1). He has been able to develop and test a discrete tide model for a 1° x 1° graded grid system in connection with a hydrodynamically defined bathymetry. The Laplace tidal equations are augmented by turbulent friction terms with novel mesh area (latitude and depth) dependent eddy-viscosity and bottom-friction coefficients. The well-known astronomical tide-generating forces are modified by effects due to solid earth tides and ocean tidal loading.

He has computed the M_2 tide in map form for four typical 30° (long.) by 50° (lat.) ocean areas. Tables III-1 and III-2 show the amplitude and phase for the Northeast Pacific. It is estimated that the tabulated tidal charts permit a prediction of the M_2-tide elevation of the ocean surface over the geoidal level with an accuracy of better than 5 cm anywhere in the open ocean and with somewhat less accuracy near rough shorelines. With the forthcoming construction of the lesser tidal constituents, the total tidal prediction error can be kept below a 10 cm bound. The lesser tidal components to be modeled next are S_2, K_1, and O_1.

III-3. Tidal Data Checks of Schwiderski Model in the Northeast Pacific

Two independent checks of Schwiderski's model against known measurements in the Northeast Pacific show remarkable agreement.

(a) Larsen and Irish (Ref. III-1a) made measurements of the M_2 tide at Cobb Seamount (46° 46.4'N; 130° 48.8'W). The comparison of their data with Schwiderski's prediction is shown in Table III-3.

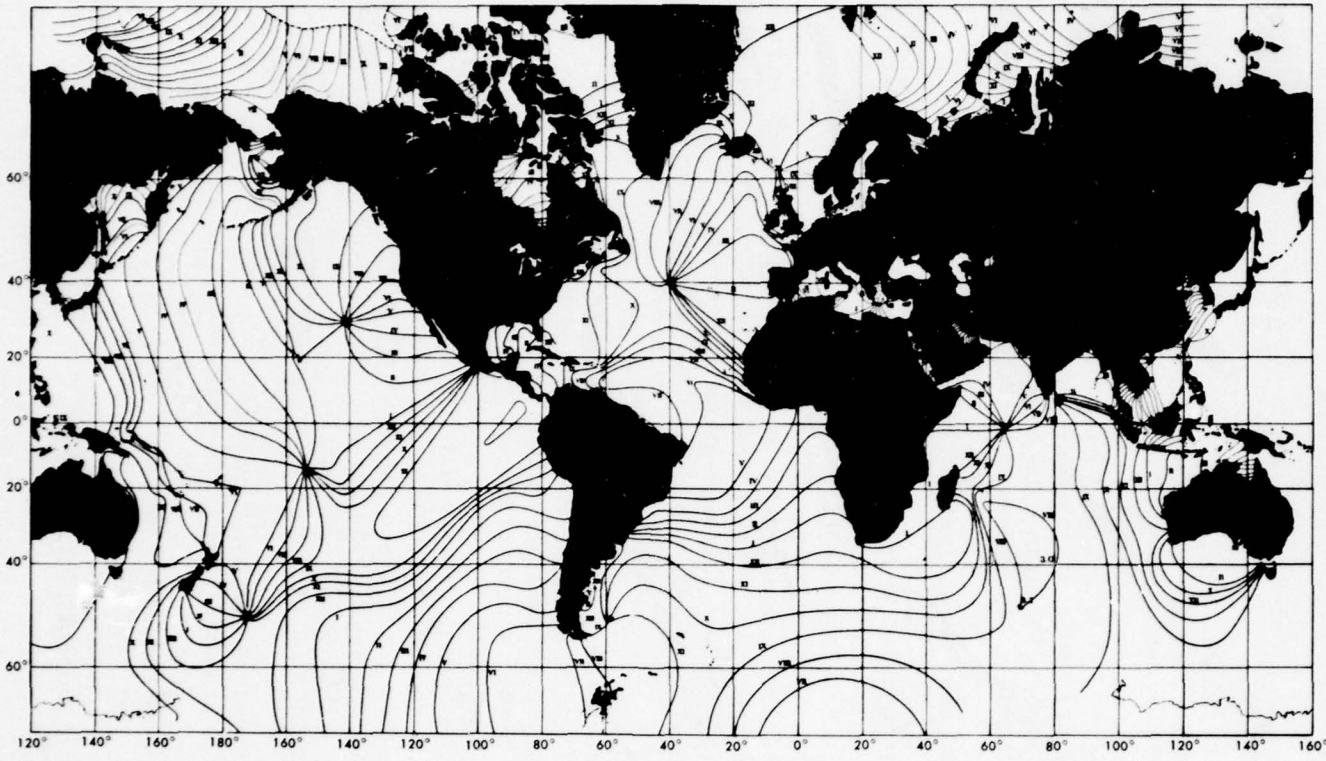

Figure III-1. Semidiurnal cotidal lines of the World Ocean, according to R.A. Harris. [from H. Poincaré, 1910, Lecons de Mécanique Celeste, Vol. 3, Paris (Gauthier-Crofts) and Ref. III-2]

Table III-1. M_2 tidal amplitudes, ξ, in centimeters, of the Northeastern Pacific Ocean. (from Ref. III-1)

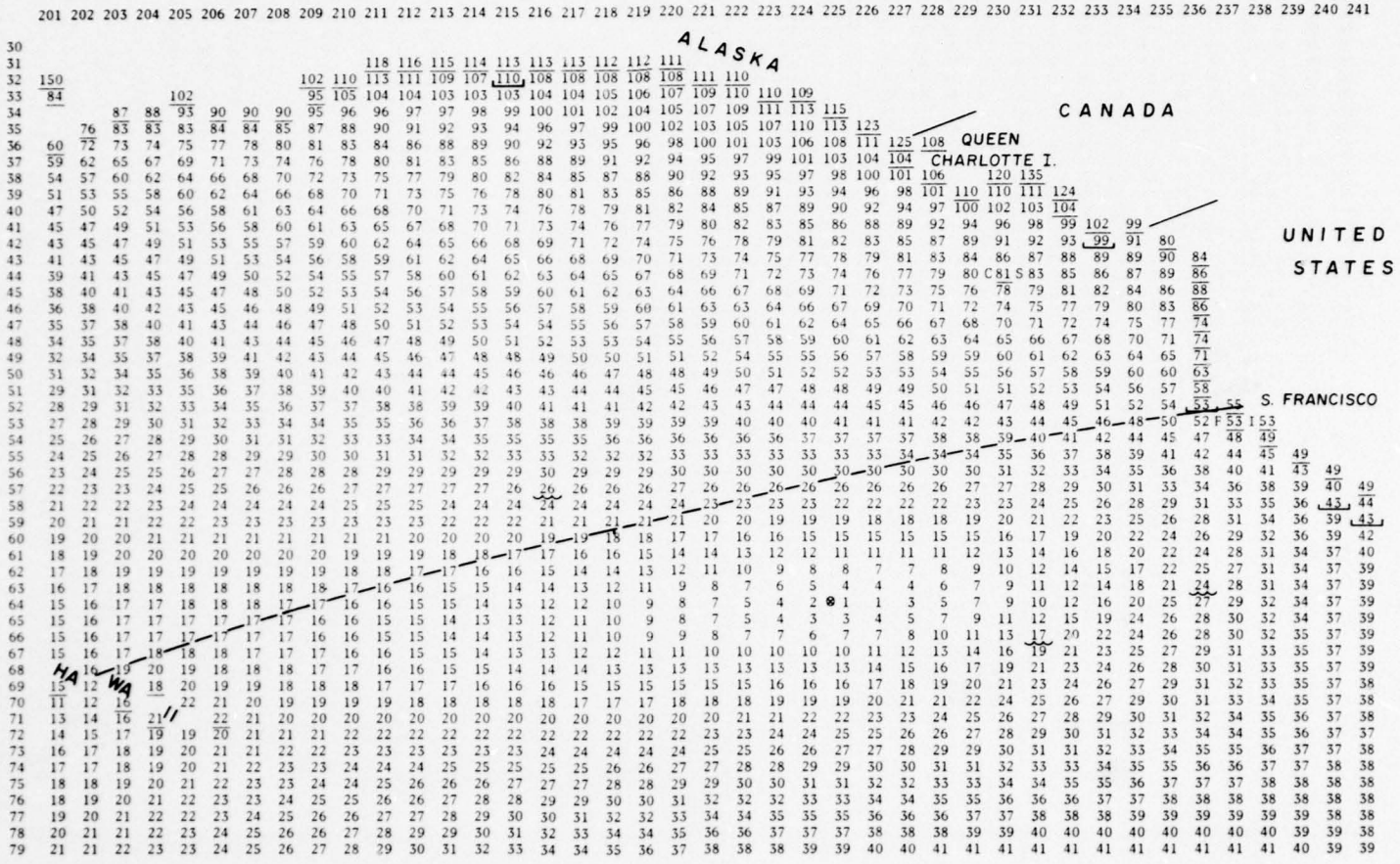

Table III-2. M_2 tidal phases, δ, in degrees, of the Northeastern Pacific Ocean. (from Ref. III-1)

	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241
30																																								
31											288	286	285	284	283	283	282	282	281	280																					
32	345								301	295	292	290	288	286	284	284	283	282	281	280	279	279																			
33	344				318				308	297	294	291	289	286	286	285	283	282	281	280	279	278	278	277																	
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35		322	317	313	309	306	303	301	299	296	294	292	289	287	285	283	282	280	279	277	276	274	272	271	269	269															
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39	316	313	310	307	304	301	298	296	293	291	288	286	284	282	280	278	276	274	272	270	269	267	265	263	261	260	258	256	258	253	250	248									
40	313	310	307	304	301	298	296	294	292	289	287	285	283	280	278	276	274	272	271	269	267	265	263	261	260	258	256	254	252	250	248	245									
41	310	307	305	302	299	297	295	292	290	288	286	283	281	279	277	275	273	271	269	267	266	264	262	260	258	256	254	252	250	248	246	244	243	241							
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46	300	298	296	294	291	289	288	286	284	282	280	278	276	274	272	270	268	266	264	262	260	258	256	254	252	250	248	245	243	241	239	237	235	233	231	233					
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63	320	320	319	319	318	318	317	316	315	314	313	312	310	308	306	304	302	301	298	295	290	283	274	261	241	213	186	169	158	151	145	140	135	133	132	130	130	131	130	130	129
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65	330	330	331	331	331	332	332	332	332	331	331	331	331	330	330	330	330	331	334	338	343	350	1	21	51	77	92	100	104	106	105	109	112	114	116	118	119	120	120	121	121
66	334	336	337	338	339	340	340	341	341	341	341	342	342	343	344	346	349	353	359	6	15	26	39	53	67	77	85	92	96	103	106	108	109	111	113	114	115	116	117	118	
67	336	342	343	345	347	348	349	350	350	350	351	351	352	353	355	356	359	3	7	13	19	27	36	46	54	63	71	79	85	91	97	100	102	104	106	108	110	111	112	113	114
68	HA	356	348	351	355	357	358	359	360	360	0	1	2	3	5	7	9	13	17	22	26	34	41	48	55	62	68	74	80	85	90	93	96	99	101	103	105	107	108	110	111
69	47	23	WA	11	4	5	7	8	8	9	9	10	11	12	13	15	17	20	24	28	33	38	44	49	55	61	66	71	76	81	85	88	91	94	96	99	101	103	105	106	108
70	53	46	62		8	12	15	16	16	16	16	17	18	19	20	21	24	26	29	33	37	41	46	50	55	60	64	69	73	77	80	84	87	90	92	94	97	99	101	103	105
71	56	53	53	55	//	31	26	24	23	22	22	22	23	24	25	27	28	31	33	36	40	43	47	51	55	59	62	66	70	73	77	80	83	86	88	91	93	95	97	99	102
72	58	56	54	52	47	38	34	31	29	28	27	27	28	28	29	30	32	34	36	39	41	44	48	51	54	57	61	64	67	70	74	77	80	82	85	87	89	91	93	96	98
73	61	57	55	52	47	42	39	36	34	32	32	31	31	32	32	33	35	36	38	40	42	45	48	51	53	56	59	62	65	68	71	74	76	79	81	83	85	88	90	92	95
74	64	60	56	53	49	45	42	42	38	36	35	35	34	34	35	36	37	38	40	41	43	45	47	50	52	55	58	60	63	66	68	71	73	75	78	80	82	84	86	89	91
75	67	62	58	55	51	48	45	43	41	39	38	37	36	36	36	37	38	39	40	42	43	45	47	49	51	54	56	59	61	63	66	68	70	72	74	77	79	81	83	86	88
76	69	64	60	56	53	50	47	45	43	42	40	39	38	37	37	38	39	40	41	42	43	45	47	49	51	53	55	57	59	61	63	65	67	69	72	74	76	78	80	83	85
77	70	65	61	58	54	51	49	47	45	43	42	40	40	39	39	39	40	41	42	43	44	45	46	48	50	51	53	55	57	59	61	63	65	67	69	71	73	75	77	79	82
78	71	67	63	59	58	53	50	48	46	44	43	42	41	40	40	40	41	41	42	43	44	45	46	47	49	51	52	54	56	57	59	61	63	64	66	68	70	72	74	76	79
79	73	69	65	61	58	54	52	50	48	46	44	43	42	42	41	41	41	42	42	43	44	44	46	47	48	50	51	53	54	56	57	59	60	62	64	66	68	70	72	74	76

ALASKA

CANADA

QUEEN CHARLOTTE I.

UNITED STATES

S. FRANCISCO

UNIVERSITY OF WASHINGTON · APPLIED PHYSICS LABORATORY

KEY TO TABLES III-1 AND III-2

M = Longitude East (°)

N = Colatitude (°)

ξ = Amplitude (cm) = half range between high and low water.

δ = Phase (°) = arrival time (1° = 2.070 min.) of tidal crest after the moon's passage over Greenwich meridian.

⊗ = Circled cross marks amphidromic point of zero amplitude.

Subbars mark empirical tide input values.

Subbrackets mark observed near-shore deep-sea input data.

Wavy underlines mark off-shore deep-sea tide gauge stations with observations listed in Tables 4a and b (see also Tables 3 and 2). [*tables in Ref. III-1*]

Estimated accuracy: about 5 cm in open ocean.

Table III-3. M_2 tide component at Cobb Seamount.

	Larsen and Irish (measured)	Schwiderski (predicted)
Amplitude	81.07 cm	82.1 cm
Phase	242.0°	245.0°

(b) Figure III-2 shows the M_2 cotidal chart from Munk, Snodgrass, and Wimbush (Ref. III-3a,b). This chart places the position of the Northeast Pacific M_2 amphidrome at 27°N, 135°W. Schwiderski's chart places this amphidrome at 26°N, 135° 30'W. The figure shows, in addition to the cotidal lines, corange contours, which are lines of equal tide height with respect to the amphidrome. Both the magnitude and the direction of the tidal current vector are shown.

III-4. Tidal Currents Along the Oahu to San Francisco Path

Schwiderski has calculated the M_2 tidal current components and the tidal heights and phases for the author for four points on the Oahu to San Francisco path (see Figure III-3). These are listed in Table III-4.

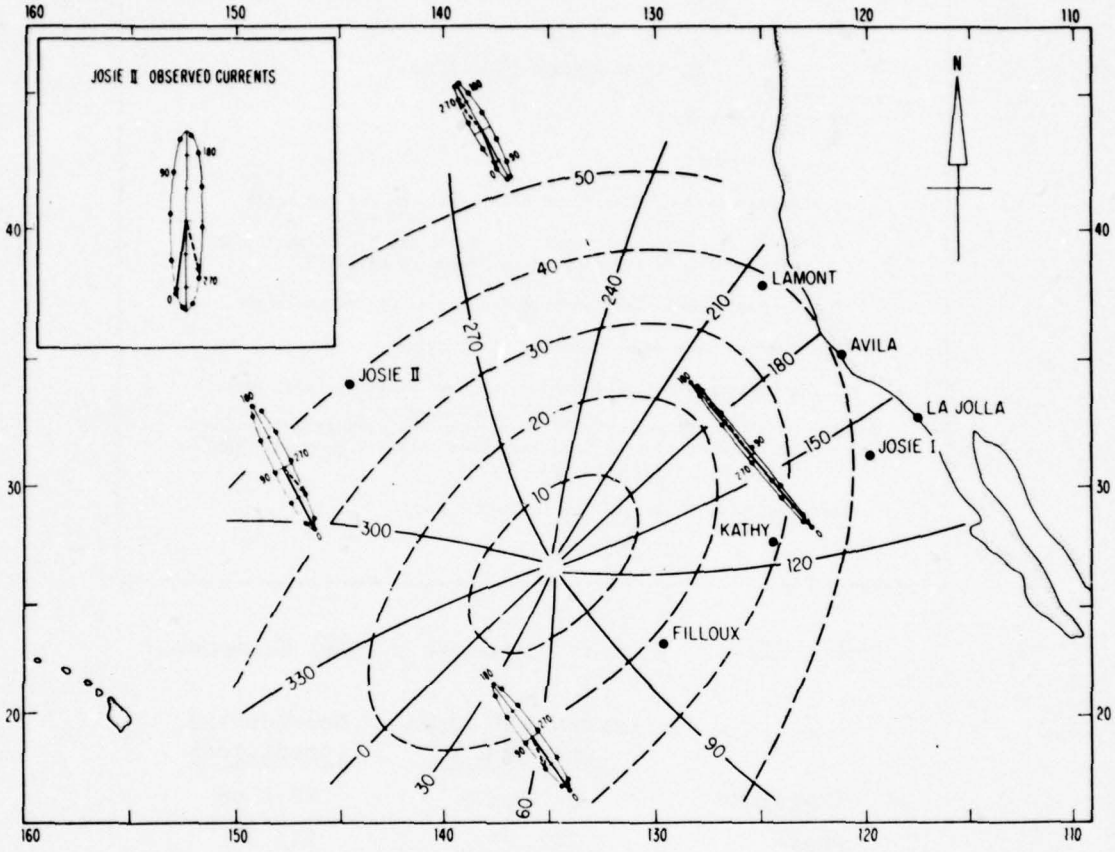


Figure III-2. *M_2 cotidal chart. (from Munk, et al., Ref. III-3a; reproduced with permission) Lines of equal amplitude H cm and of equal Greenwich epoch G° are shown by the dashed and solid curves. Ellipses refer to the computed tidal currents at the ellipse center. The heavy arrow toward G = 0 is the tidal current when the moon is over the Greenwich meridian. The dots indicated for 30°, 60°, ..., give the end point of the current vector for other Greenwich epochs. The dashed arrow is the current vector at the time of local high tide. The inset shows the observed currents at JOSIE II. Tick marks on the major axis of the ellipses correspond to current speeds at intervals of 1 cm/sec.*

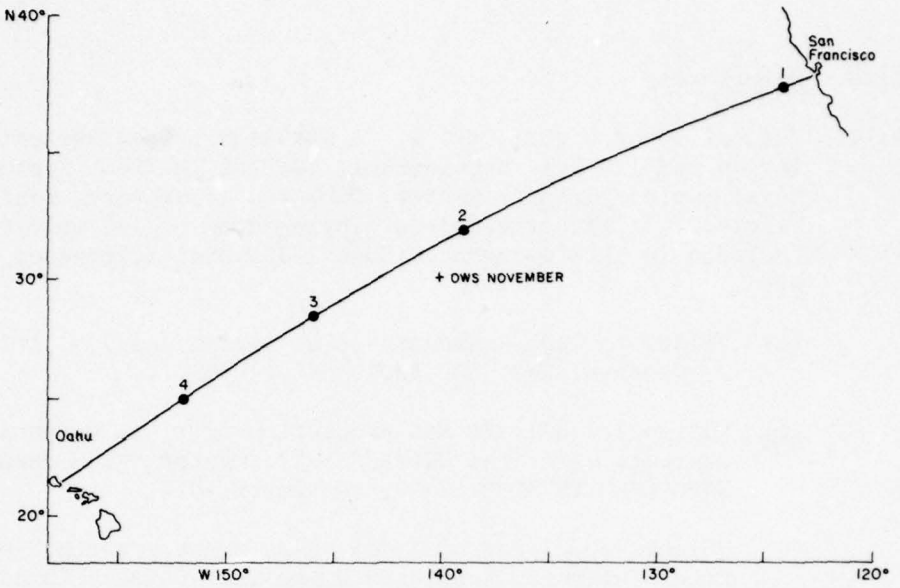


Figure III-3. Stations along acoustic path at which tidal currents have been computed. (See Table III-4.)

Table III-4. M_2 ocean tide constants.

Station Latitude, Longitude	$A_u\left(\frac{cm}{sec}\right)$	δ_u(°)	$A_v\left(\frac{cm}{sec}\right)$	δ_v(°)	A_ξ(cm)	δ_ξ(°)
*Pacific St. #1	0.64		3.54		52.1	
37°23.2'N 124°W		303.8		53.9		201.3
Pacific St. #2	0.39		2.12		21.5	
31°56.1'N 139°W		272.7		71.2		257.6
Pacific St. #3	0.59		1.81		15.9	
28°28.2'N 146°W		270.4		72.0		298.7
Pacific St. #4	0.75		1.71		16.6	
25°19.2'N 152°W		275.6		75.4		333.4

where (A_u, δ_u) = Amplitude and phase of east velocity u

(A_v, δ_v) = Amplitude and phase of north velocity v

(A_ξ, δ_ξ) = Amplitude and phase of tidal height ξ

All phases δ relative to Greenwich meridian for which

$\delta = 1° = 2.0701$ min (time)

*Marked velocity constants unreliable.

III-5. References

III-1. "Global ocean tides, Part 1: A detailed hydrodynamical interpolation model," E.W. Schwiderski, NSWC/DL TR-3866, September 1978, Naval Surface Weapons Center, Dahlgren Laboratory, Dahlgren, Virginia. A rather complete bibliography of 140 references is included in this document. Some additional references not included are:

(a) "Tides at Cobb Seamount," L.H. Larsen and J.D. Irish, J. Geophys. Res. 80, 1691-1695 (1975).

(b) "Harmonic analysis and prediction of tidal heights and currents using the UNIVAC 1108 computer," W.H. Beatty III, NAVOCEANO TN 3700-68-77, September 1977.

(c) "Global modelling of tides on an elastic earth," M.E. Parke, Proc. Internat. Long Wave Symposium, Ottawa, Canada, 1978.

(d) "M_2, S_2, K_1 models of the global ocean tide on an elastic earth," M.E. Parke and M.C. Hendershott, Symposium on Interaction of Marine Geodesy and Ocean Dynamics, Miami, Florida, October 1978.

(e) "A computer software system for the generation of global ocean tides including self-gravitation and crustal loading effects," R.H. Estes, Report X-920-77-82, April 1977, Goddard Space Flight Center, Greenbelt, Maryland.

III-2. See also An Introduction to Physical Oceanography, W.S. von Arx (Addison-Wesley Publishing Co., Reading, Massachusetts, 1974).

III-3. (a) "Tides off-shore: transition from California coastal to deep-sea waters," W.H. Munk, F.E. Snodgrass, and A.M. Wimbush, Geophys. Fluid Dynamics 1, 161-235 (1970).

(b) M_2 Amphidrome in the Northeast Pacific," J. Irish, W. Munk, and F. Snodgrass, Geophys. Fluid Dynamics 2, 355-360 (1971).

General: Dr. E.W. Schwiderski furnished the author basic information and reports and also made special calculations of tidal currents.

IV. BOTTOM TOPOGRAPHY OF THE ACOUSTIC PATH

IV-1. Effects of Bottom Topography on Acoustics

Topographic features may contribute to multipath, reverberation and reduced signal levels. Topographic characteristics relate to the many charted and uncharted seamounts in the Pacific. The longer the acoustic path, the greater the probability of multipaths due to reflections from seamounts. A presentation of this situation in the extreme is shown in Figure IV-1, taken from Sheehy and Halley (Ref. IV-1). In 1955 they monitored the arrivals from a nuclear explosion in the Southeast Pacific several hundred miles southwest of San Diego. Signals were received at three locations: Kaneohe, Pt. Sur, and Pt. Arena. The reflected signals from islands and seamounts were recorded for 2 hours at Kaneohe, and for 4 hours at Pt. Sur. There were more unknown reflectors than there were identifiable ones.

IV-2. Sound Channel Signal Blockage

Another effect of seamounts lying in the deep sound channel of the acoustic path is sound channel signal blockage. Dr. Henry Fleming of NRL furnished Figure IV-2 as an example, based on actual measurements for another path. The acoustic ray systems shown have been calculated for two cases of seamount configuration in a 1700 km path (not ours) for a frequency of 110 Hz. In the case of the upper figure, no signal was received; in the lower figure a signal was received. The positioning of the transmitter in depth and range would appear to be quite important with respect to the density of rays clearing the seamounts.

IV-3. Bottom Topography of the Acoustic Path

The NORDA SYNBAPS program (Ref. IV-2) has provided 40 great circle radial bathymetric profiles spaced 1° apart in bearing from Oahu, Hawaii, to the West Coast and approximately centered on the San Francisco radial. The bearings of these radials are shown in Figure IV-3.

SYNBAPS is the acronym for "synthetic bathymetric profiling system." The bathymetric information is provided in both machine-plot and listing form. The listing gives the depth in meters at 1-mile intervals. A plot is shown in Figure IV-4 for the Oahu to San Francisco path. Blockage effects are not expected to be severe for this path. However, the path skirts seamount chains, and a slight change in path orientation could produce severe blockage. If profiles are needed for specific paths, these can be provided within 48 hours.

Data can be provided on magnetic tape also. In preparing the historical oceanographic data of temperature, salinity and sound speed, bathymetry for the Makapuu Point to San Francisco path will also be provided from the Scripps Institution of Oceanography data file. Ref. IV-3 provides contours for the North Pacific Ocean and can be used also.

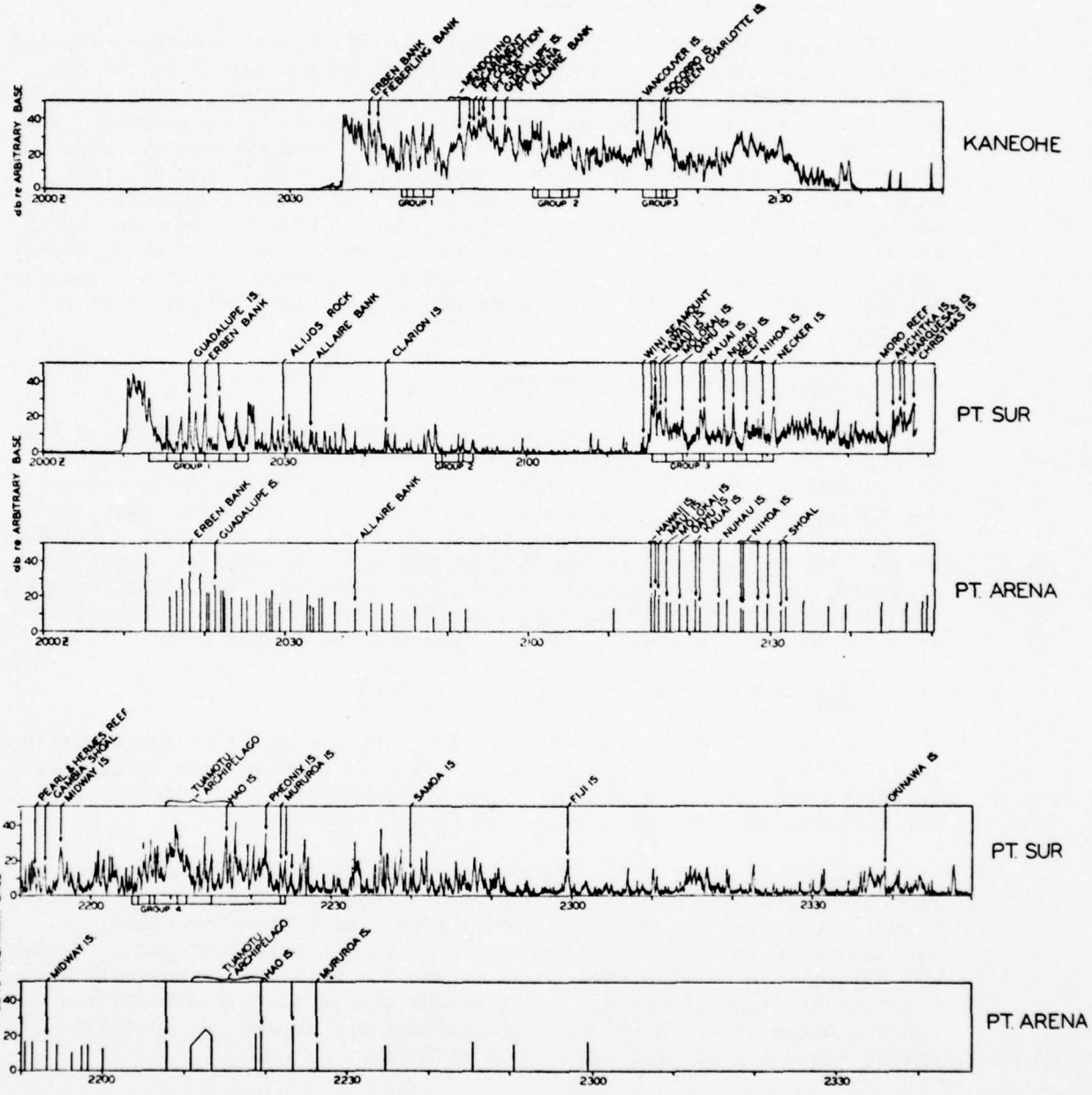
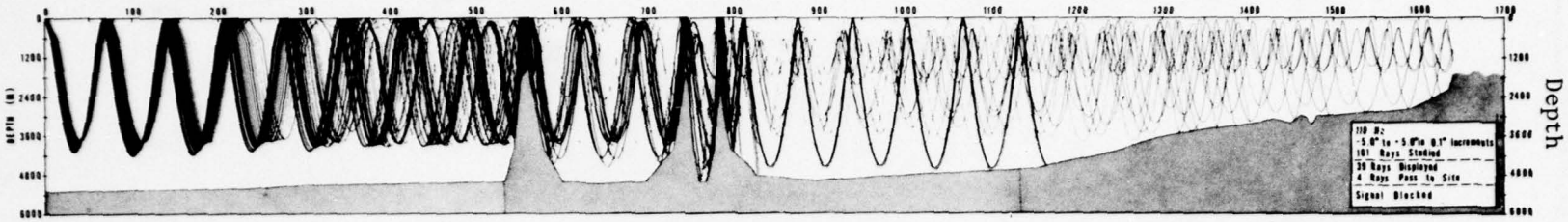
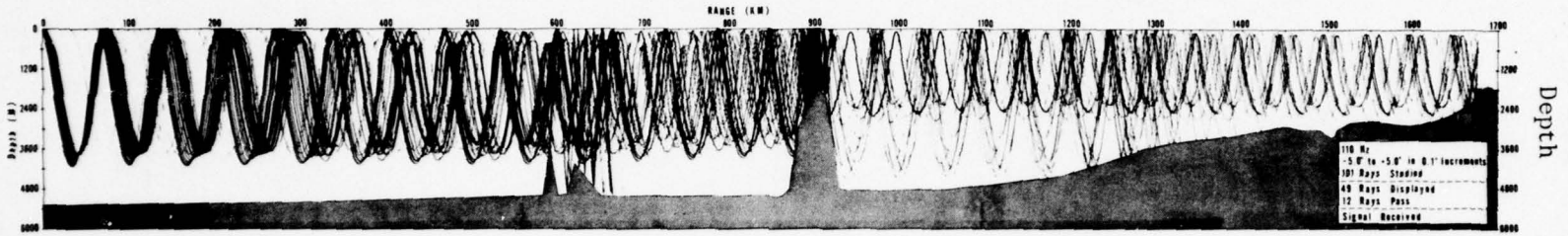


Figure IV-1. Received signals showing reflections from various land masses. (from Ref. IV-1; reproduced with permission)



SIGNAL BLOCKED

101 rays studied
39 rays displayed
4 rays pass to site



SIGNAL RECEIVED

101 rays studied
49 rays displayed
12 rays pass to site

Figure IV-2. Effect of seamounts on acoustic signal transmission: range of 1700 km; 110 Hz. (provided by H.S. Fleming, Naval Research Laboratory; not the path of this study)

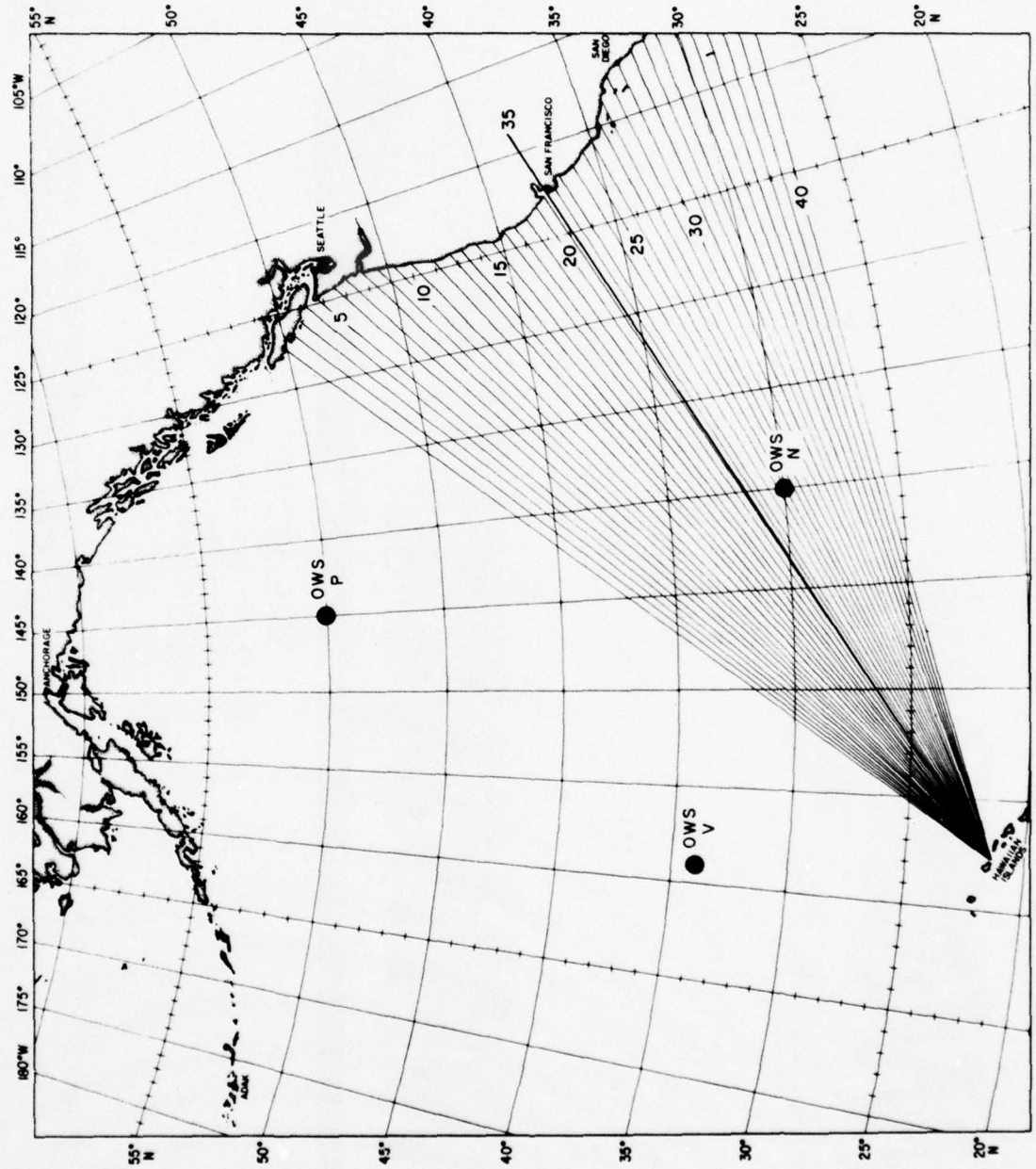


Figure IV-3. Index of 40 SYNBAPS profile runs; locations are approximate.

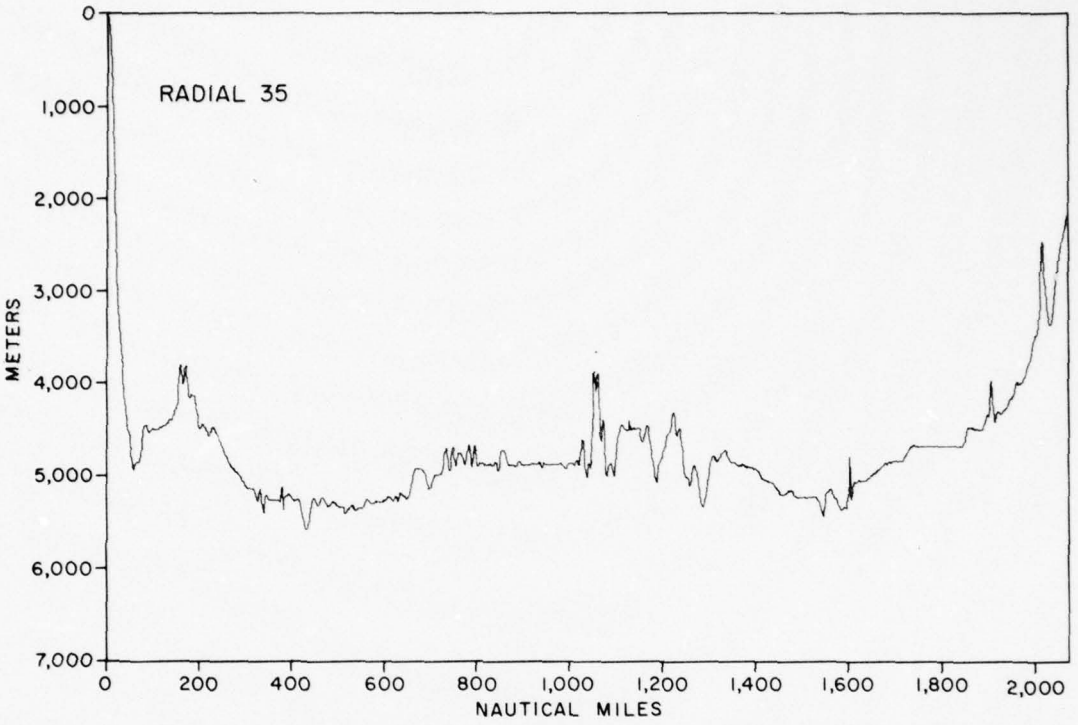


Figure IV-4. SYNBAPS bathymetric profile--Makapuu Point, Hawaii, to San Francisco.

IV-4. References

IV-1. "Measurements of the attenuation of low frequency underwater sound," M.J. Sheehy and R. Halley, J. Acoust. Soc. Am. 29, 464-469 (1957).

IV-2. "Synthetic bathymetric profiling system," NAVOCEANO TR233, February 1973, DMA Supply Depot, Philadelphia, Pennsylvania.

IV-3. "Bathymetric atlas of the North Pacific Ocean," N.O. Pub. 1301-2-3, 1973, NAVOCEANO, Washington, D.C.

General: Mr. Roger Van Wyckhouse of NORDA generously provided SYNBAPS listings and plots for the required radials.

V. SOUND SPEED PROVINCES AND OCEAN WATER MASSES

V-1. Acoustic Properties of the Oahu to San Francisco Path

Figure V-1 shows, for January, the average depth of the mixed layer or surface sound channel, the critical depth, and the depth of the sound channel axis along the path. These were determined from Dr. Eugene Podeszwa's "Sound Speed Profiles for the North Pacific Ocean," Ref. V-1. In preparing this atlas, Podeszwa tried to find the fewest number of independent areal subdivisions that would furnish this information on a monthly basis with an acceptable error in sound speed. For our path the number of independent provinces turns out to be eight, corresponding to the eight sections between the points shown in the figure. The grouping of these eight provinces among the three water masses of the path is also shown in this figure. Dividing the acoustic path length, 3835 km, by eight, gives an average length of about 480 km for a province. This suggests that we may be talking here about stable mesoscale features. Mesoscale features are discussed in Section VII-1.

V-2. Sound-Speed-Profile Provinces for the Central and North Pacific Ocean

Figure V-2 shows how the acoustic path traverses eight sound-speed-profile provinces compiled for the depth interval 0 to 4500 ft (Ref. V-1). It can also be seen that the shapes of the provinces follow those of the current systems and water masses: westerlies, California Current, easterly trade winds, and a diagonal wind shear and current line passing through the Hawaiian Islands. Table V-1 shows how the Podeszwa sound-speed-profile province classification fits into the North Pacific water mass classification using the T-S diagram classification of Figure II-2.

Table V-2 lists three acoustic parameters along the path: mixed layer depth, deep sound channel axis depth, and critical depth. The critical depth is taken as that depth where the sound speed equals the surface sound speed. It is important in specifying convergence zone propagation for a near-surface source. Note that Podeszwa's tables do not allow us to describe the seasonal dependence of the sound channel axis depth. However, this information may be gotten from the summaries of historical data obtained from the National Ocean Data Center.

V-3. Summary of Historical Monthly Sound Speed Data

Lists of historical monthly sound speed data were provided at standard depths by the National Ocean Data Center (NODC; NOAA). The lists were provided in the 2° x 2° Modified Canadian Square (MCS) breakdown as shown in Figure V-3. The lists are shown as Tables V-3 through V-21. There is no list for MCS 1215, 2° x 2° #26 because no data existed in the NODC files for this region.

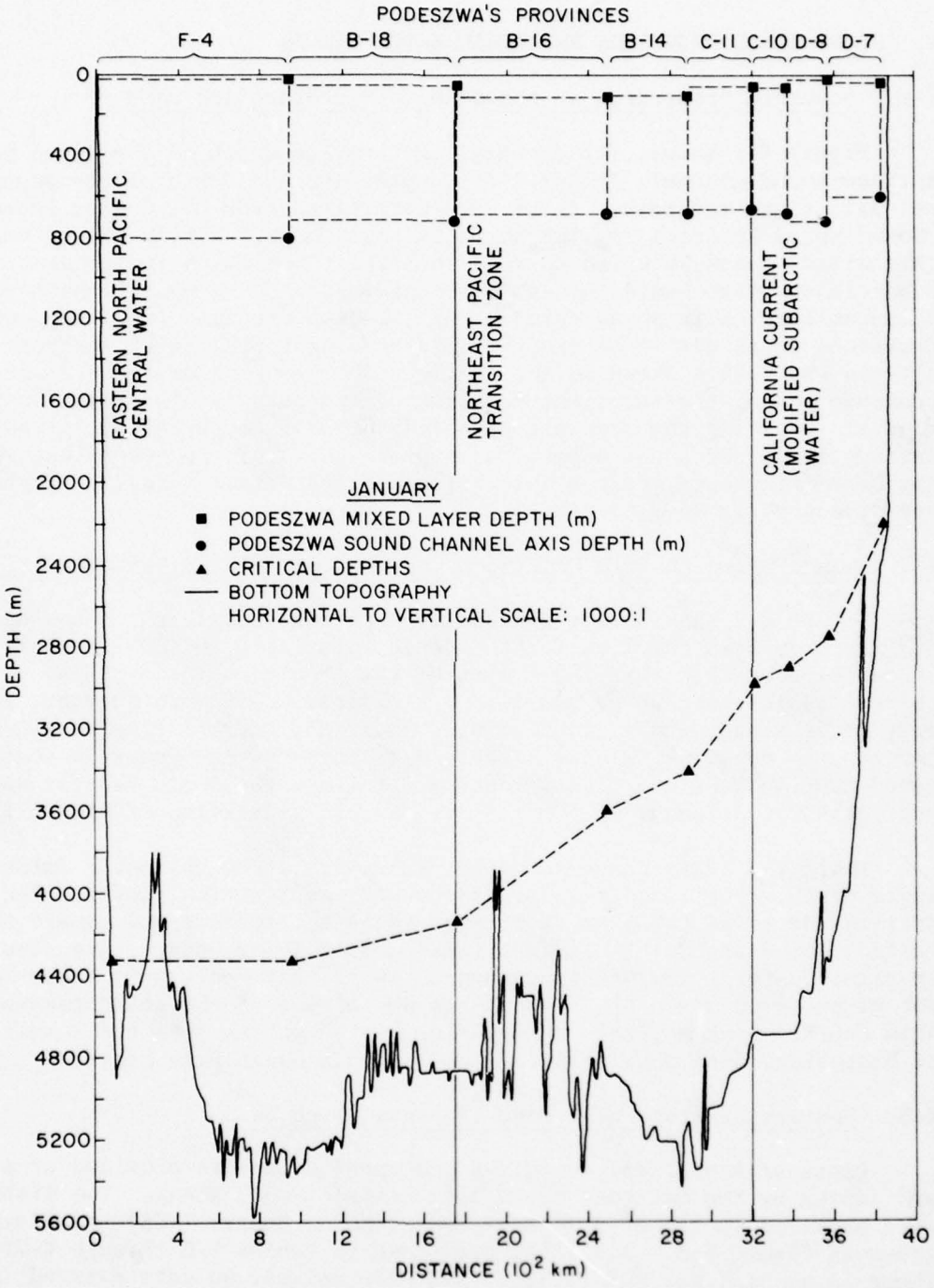


Figure V-1. Acoustic properties of path for January from Makapuu Point, Hawaii, to San Francisco.

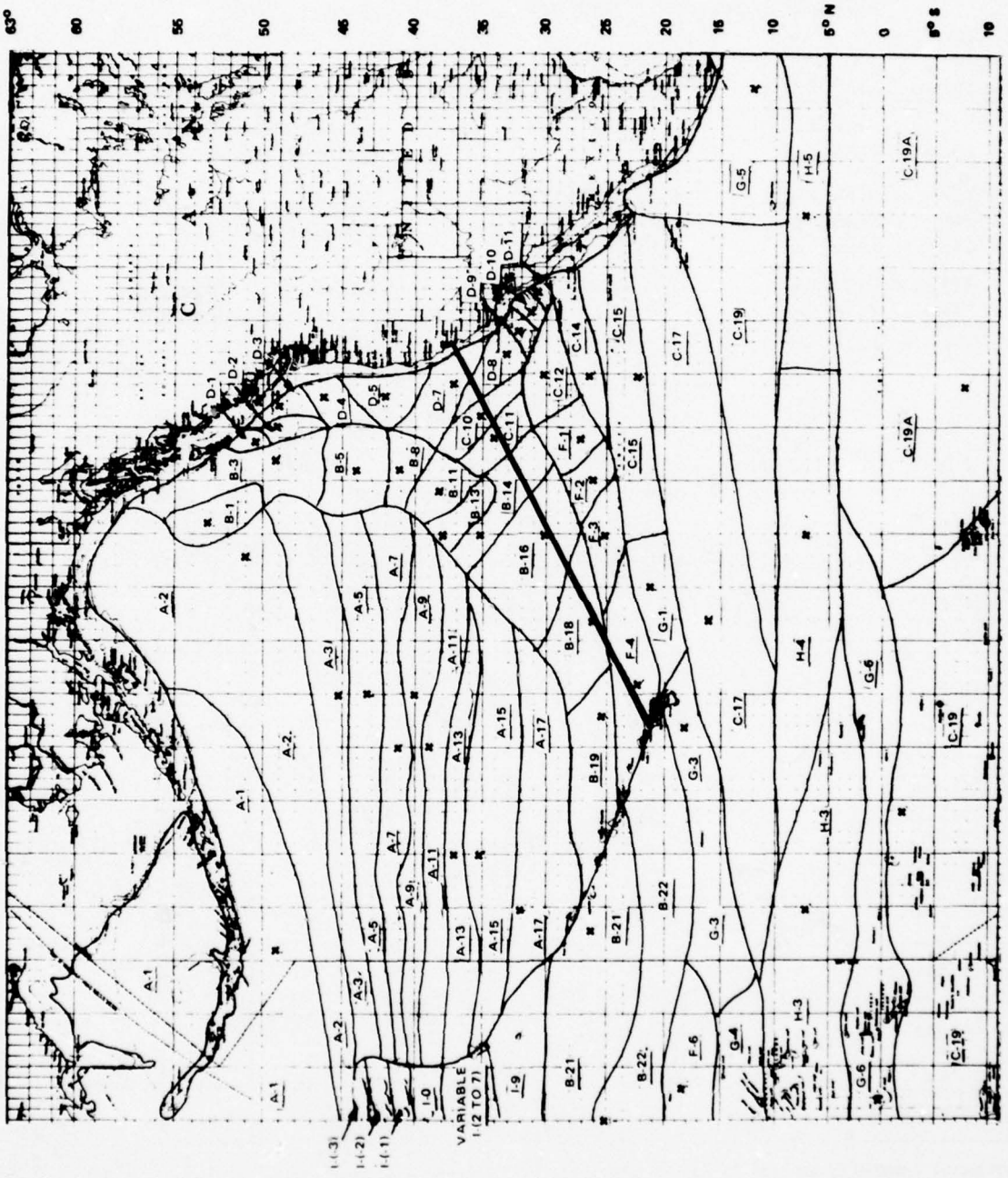


Figure V-2. Location chart of representative sound speed profile structure for Central and Eastern North Pacific Ocean from 0 to 4500 ft. (from Ref. V-1)

Table V-1. Relation between North Pacific water mass class and sound-speed-profile provinces (acoustic path between Makapuu Point, Hawaii, and San Francisco).

Distance Along Path	Sound-Speed-Profile Province (Podeszwa)	Water Mass Class
0 - 949 km	F-4	Eastern North Pacific Central Water
949 - 1755 km	B-18	
1755 - 2480 km	B-16	Northeast Pacific Transition Zone
2480 - 2889 km	B-14	
2889 - 3210 km	C-11	
3210 - 3380 km	C-10	California Current (modified subarctic water)
3380 - 3570 km	D-8	
3570 - 3835 km	D-7	

*Table V-2. Seasonal dependence of mixed layer depths, m, and critical depths, m, for Oahu to San Francisco path.**

	Podeszwa's Sound Speed Provinces								
	F-4	B-18	B-16	B-14	C-11	C-10	D-8	D-7	
Distance Along Path to Outer Boundary, km	949 km	1755 km	2480 km	2889 km	3210 km	3380 km	3570 km	3835 km	
Mixed Layer Depth, m	30.5 m	61.0 m	122 m	107 m	61.0 m	68.6 m	30.5 m	45.7 m	January
Deep Sound Channel Axis, m	807.7	731.5	701.0	685.8	670.6	685.8	731.5	609.6	
Critical Depth, m	4334	4127	3596	3398	2969	2895	2743	2194	
Mixed Layer Depth, m	76.2	45.7	107	61.0	61.0	61.0	22.9	45.7	April
Deep Sound Channel Axis, m	807.7	731.5	701.0	685.8	670.6	685.8	731.5	609.6	
Critical Depth, m	4374	4267	3383	3109	2774	2652	2743	2179	
Mixed Layer Depth, m	15.2	15.2	21.3	15.2	33.5	15.2	18.3	15.2	July
Deep Sound Channel Axis, m	807.7	731.5	701.0	685.8	670.6	685.8	731.5	609.6	
Critical Depth, m	4542	4587	3962	3901	3597	3383	3185	2850	
Mixed Layer Depth, m	30.5	33.5	45.7	30.5	38.1	24.4	30.5	27.4	October
Deep Sound Channel Axis, m	807.7	731.5	701.0	685.8	670.6	685.8	731.5	609.6	
Critical Depth, m	4572	4557	4191	4008	3566	3459	3414	3109	

*Podeszwa's tables do not provide seasonal dependence for the deep sound channel axis.

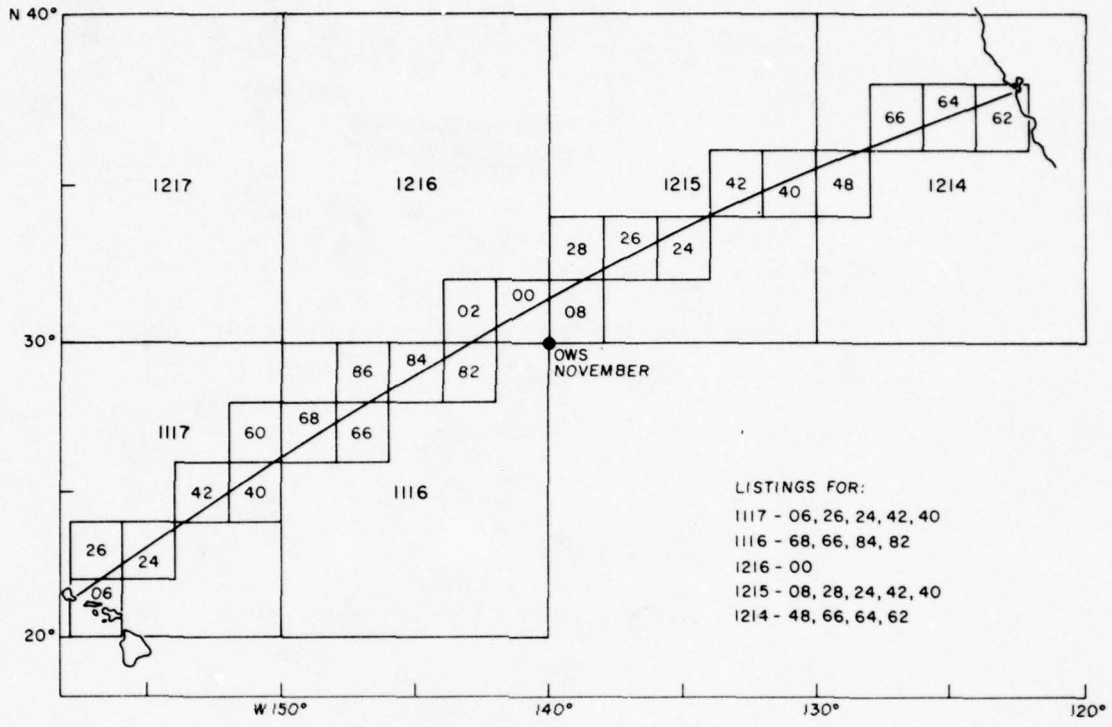


Figure V-3. Modified Canadian Square designators; Oahu to San Francisco, great circle path.

Figure V-4 shows a plot of the monthly values of mixed layer depths and the deep sound channel axis depths, based on the listings for these 2° x 2° squares. In this case there were not enough deep data to obtain monthly values of critical depths. In plotting Figure V-4, the distance of the squares along the path has been taken nominally as the distance of the square's center from Makapuu Point at 21°19'N, 157°39'W. These distances are shown on the tables of data. The geographical position of San Francisco has been taken as 37°49'N, 122°25'W. The great circle length of the entire path is 3835 km, or 2071 n. mi.

Dr. Tom Davis of NAVOCEANO has compiled digital tape listings at standard depths of historical temperature, salinity and sound speed data for four seasons on a 30 minute grid for any point in the oceans of the Northern Hemisphere. He also provides an error statement of these values. The beauty of the magnetic tape listings of sound speed is that they may be combined with synoptic XBT temperature data and surface extrapolated salinity data to provide an on-the-spot sound speed profile to the bottom. This procedure's application to this program is discussed further in the next chapter.

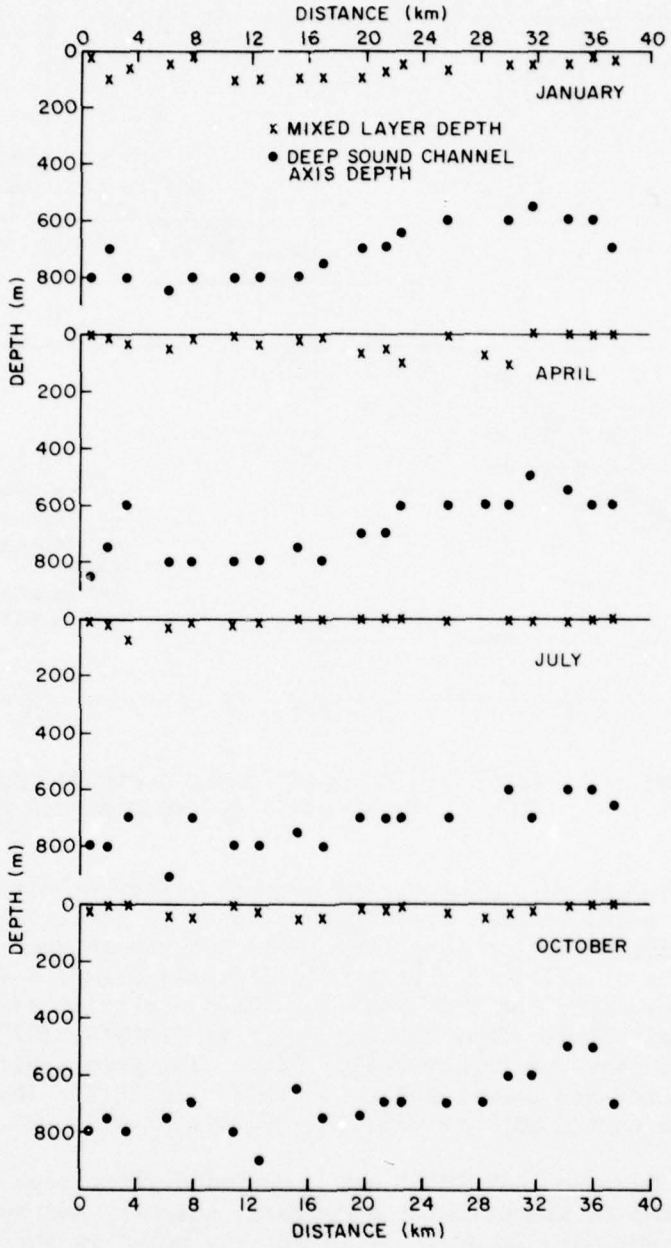


Figure V-4. Seasonal changes in mixed layer depth, m, and deep sound channel axis depth, m, for Oahu to San Francisco path; NODC historical data.

Table V-3.

10 Sq 1117 2 Sq 6 (76.0 km)*
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1533.6	1531.7	1531.9	1533.9	1534.5	1534.4	1536.4	1536.4	1536.9	1537.3	1536.6	1535.7
10	1533.7	1531.8	1531.8	1533.8	1534.5	1534.7	1536.4	1536.4	1537.0	1537.4	1536.7	1535.8
20	1533.9	1532.0	1531.7	1533.8	1534.3	1534.6	1536.3	1536.3	1537.1	1537.5	1536.7	1534.5
30	†1534.0	1532.1	1531.6	1533.8	1533.9	1534.6	1536.2	1536.1	1537.0	1537.7	1536.7	1534.8
50	1533.2	1532.4	1531.4	1533.6	1532.6	1534.4	1535.4	1536.0	1536.0	1537.6	1536.6	1534.3
75	1532.1	1531.8	1531.0	1532.9	1530.6	1533.3	1533.8	1534.0	1533.1	1534.8	1534.7	1533.8
100	1531.0	1530.4	1530.1	1531.6	1528.4	1531.3	1531.4	1531.7	1530.4	1531.9	1531.5	1532.2
125	1526.3	1528.5	1528.8	1529.4	1525.9	1528.8	1529.3	1529.7	1528.1	1529.1	1528.1	1529.7
150	1523.0	1525.4	1526.6	1526.6	1522.7	1526.1	1526.3	1527.5	1525.3	1526.3	1525.6	1527.6
200	1516.0	1517.5	1519.7	1519.8	1513.7	1518.8	1518.6	1522.3	1517.9	1519.6	1518.0	1520.3
250	1506.2	1507.7	1510.0	1509.2	1504.1	1508.8	1507.7	1513.1	1509.2	1509.3	1507.9	1510.6
300	1499.5	1500.7	1500.3	1500.1	1496.7	1500.6	1499.0	1503.4	1500.7	1500.2	1499.2	1501.5
400	1490.6	1490.3	1489.7	1489.8	1488.7	1489.7	1489.4	1490.5	1489.7	1490.3	1489.7	1488.7
500	1485.5	1486.1	1484.9	1485.0	1484.4	1484.0	1484.6	1486.2	1484.8	1485.8	1484.4	1485.1
600	1483.3	1483.6	1483.1	1483.5	1482.5	1482.5	1483.1	1483.5	1483.2	1484.0	1483.4	1482.8
700	1482.8	1483.0	1482.6	1482.9	1482.2	1482.1	1482.6	1483.3	1482.3	1483.3	1482.6	1482.1
800	†1482.6	1483.0	1482.5	1482.8	1482.3	1482.1	1482.6	1482.4	1482.3	1483.0	1482.7	1482.0
900	1482.7	1483.0	1482.6	1482.8	1482.5	1482.8	1482.6	1482.5	1482.6	1483.2	1483.0	1483.0
1000	1483.0	1483.4	1483.2	1483.1	1482.7	1483.1	1483.0	1482.2	1483.0	1483.6	1483.3	1483.5
1100	1483.5	1483.4	1484.0	1483.5	1483.1	1483.4	1483.4	--	1483.4	1484.0	1483.7	--
1200	1484.3	1484.0	1484.6	1484.2	1483.7	1483.9	1484.1		1483.9	1484.5	1484.4	
1300	1485.1	1484.7	1485.2	1484.8	1484.5	1484.6	1484.9		1484.7	1485.0	1484.6	
1400	--	1485.4	1486.0	1485.5	1485.2	1485.3	1485.7		1485.5	1485.2	1485.4	
1500		--	--	1486.4	1486.1	--	1486.6		1486.4	1486.1	1486.2	
1750				--	--	1488.8	1488.4		--	--	--	
2000						1491.7	1491.3					
2500						1498.5	--					
3000						--						
4000												
5000												
No. of Surface Values	2	7	32	20	51	9	31	32	13	18	10	2

*Distance from Makapuu Pt. to center of square
†The maximum and minimum sound velocities are underlined, showing the depths of the mixed layer and the sound channel axis, respectively.

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Table V-4.

10 Sq 1117 2 Sq 26 (199 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1531.2	1529.5	1530.3	1530.5	1532.3	1533.4	1535.3	1535.2	1536.2	1535.8	1533.9	1532.1
10	1531.4	1529.6	1530.4	1530.6	1532.6	1533.4	1535.5	1535.4	1536.4	1535.9	1534.0	1532.3
20	1531.6	1529.7	1530.5	1530.4	1532.4	1533.2	1535.6	1535.5	1536.5	1535.7	1534.0	1532.3
30	1531.8	1529.9	1530.6	1530.3	1532.2	1533.2	1535.4	1535.6	1536.3	1535.6	1534.1	1532.3
50	1532.1	1530.2	1530.8	1530.0	1531.5	1532.4	1535.1	1535.5	1535.5	1535.3	1534.4	1532.3
75	1532.5	1530.8	1530.4	1529.7	1530.1	1531.2	1532.3	1533.9	1533.6	1533.1	1532.2	1532.2
100	1532.6	1530.8	1529.6	1529.0	1528.5	1529.9	1530.0	1531.4	1531.8	1530.6	1530.5	1531.1
125	1531.0	1528.9	1527.7	1526.9	1525.7	1528.7	1528.3	1529.6	1528.9	1528.3	1526.6	1527.8
150	1526.1	1526.2	1524.9	1524.0	1524.1	1525.8	1526.3	1527.5	1525.7	1526.2	1523.5	1526.1
200	1519.7	1519.7	1518.3	1517.4	1517.5	1519.6	1520.1	1522.5	1519.6	1519.9	1516.4	1517.8
250	1511.0	1510.7	1509.6	1508.8	1507.5	1511.6	1510.8	1515.2	1511.5	1511.4	1508.2	1507.0
300	1503.0	1503.1	1501.9	1501.7	1500.2	1503.5	1501.8	1506.0	1505.0	1503.3	1502.2	1501.5
400	1493.1	1492.0	1491.7	1491.1	1490.4	1491.4	1491.5	1493.6	1492.9	1492.8	1495.1	1491.8
500	1485.8	1485.2	1485.4	1484.7	1484.0	1486.3	1485.9	1486.5	1485.5	1485.7	1487.2	1485.1
600	1482.2	1483.0	1482.5	1482.5	1481.3	1482.7	1483.1	1482.0	1482.2	1482.7	1482.9	1482.6
700	1482.0	1482.3	1481.9	1481.9	1481.2	1481.6	1482.2	1481.4	1482.7	1482.0	1482.3	1482.4
800	1482.1	1482.0	1481.9	1481.9	1481.3	1481.4	1482.0	1481.2	1482.5	1482.0	1481.8	1482.3
900	1482.5	1481.9	1482.2	1482.3	1481.6	1481.9	1482.4	1481.7	1482.7	1482.4	1481.9	1482.5
1000	1482.9	1482.3	1482.5	1482.7	1482.0	1482.7	1482.9	1482.2	1482.4	1482.8	1482.3	1482.9
1100	1483.4	1483.0	1483.0	1483.1	1482.6	1483.3	1483.4	1482.7	1482.8	1483.3	1482.6	1483.3
1200	1484.0	1483.8	1483.6	1483.7	1483.3	1483.9	1484.0	1483.3	1483.3	1483.9	1483.0	1483.8
1300	1484.7	1484.4	1484.4	1484.4	1484.1	1484.7	1484.5	1484.1	1484.1	1484.6	1483.7	1484.4
1400	1485.4	1485.3	1485.2	1485.2	1485.0	1485.5	1485.3	1485.0	1485.0	1485.7	1484.7	1485.1
1500	1486.2	1486.3	1486.1	1486.1	1486.3	--	1486.3	--	1485.9	--	1486.0	--
1750	--	1488.9	--	--	1488.9		1488.9		--		1488.8	
2000		1491.8			1491.8		1491.7				1491.6	
2500		1498.6			1498.6		1498.4				1498.5	
3000		--			1506.4		1506.3				1506.2	
4000					--		1523.5				--	
5000							--					
No. of Surface Values	2	6	11	4	5	5	25	7	4	4	3	2

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Table V-5.

10 Sq 1117 2 Sq 24 (331 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	--	1528.9	1529.1	1530.0	1530.4	1533.0	1535.1	1535.2	1536.3	1535.5	1534.9	--
10		1529.1	1529.3	1530.2	1530.4	1533.0	1535.3	1535.4	1536.4	1535.6	1535.1	
20		1529.1	1529.4	1530.3	1530.2	1533.0	1535.5	1535.6	1536.5	1535.4	1535.3	
30		1529.1	1529.6	1530.3	1530.1	1532.9	1535.6	1535.7	1536.5	1535.2	1535.5	
50		1529.3	1529.9	1530.1	1529.5	1531.9	1536.0	1534.9	1535.9	1534.5	1535.7	
75		1529.4	1529.8	1529.8	1529.1	1529.8	1536.1	1532.5	1532.3	1532.4	1532.4	
100		1529.1	1529.2	1528.9	1528.7	1528.2	1532.7	1529.7	1529.4	1530.0	1527.4	
125		1527.3	1527.1	1527.5	1527.9	1526.5	1531.7	1527.6	1527.6	1527.9	1524.9	
150		1524.6	1524.6	1525.9	1526.3	1524.4	1530.7	1525.5	1525.6	1525.5	1522.2	
200		1518.0	1519.3	1519.8	1520.9	1518.2	1526.1	1519.5	1519.3	1518.7	1516.2	
250		1511.0	1510.5	1511.0	1512.6	1510.6	1516.2	1510.8	1510.0	1509.4	1506.0	
300		1504.2	1502.7	1502.8	1505.3	1503.6	1503.1	1502.6	1502.6	1501.8	1498.0	
400		1494.9	1491.5	1492.5	1494.4	1493.1	1492.3	1492.0	1491.9	1492.3	1489.0	
500		1486.7	1485.5	1485.2	1487.6	1485.9	1487.6	1484.6	1485.3	1485.5	1483.2	
600		1482.8	1482.5	1481.5	1483.5	1482.7	1485.4	1482.3	1482.7	1482.3	1481.2	
700		1482.3	1481.5	1481.7	1482.3	1482.2	1484.6	1482.1	1482.6	1481.7	1481.3	
800		1482.1	1481.6	1481.9	1481.8	1482.0	--	1482.2	1482.6	1481.6	1481.6	
900		1482.2	1482.2	1482.1	1482.0	1482.3		1482.5	1482.8	1482.0	1481.9	
1000		1482.1	1482.7	1482.4	1482.5	1482.1		1482.9	1483.5	1482.3	--	
1100		1482.9	1483.2	1483.7	1483.2	1483.3		1483.4	1484.0	1482.7		
1200		1483.8	1483.6	1484.3	1483.8	1484.3		1484.2	1484.8	1483.2		
1300		1484.6	1484.5	1485.0	1484.6	1485.0		1485.0	1485.3	1483.9		
1400		1485.5	1485.3	1485.9	1485.3	1485.8		1485.6	1486.0	--		
1500		1486.3	1486.2	--	1486.6	--		1486.3	1486.8			
1750		--	--		1489.1			1488.6	1489.4			
2000					1491.9			1491.7	1492.2			
2500					1498.6			1498.5	1498.7			
3000					1506.4			1506.3	--			
4000					--			1523.5				
5000								--				
No. of Surface Values	0	4	7	4	5	10	1	3	5	2	2	0

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Table V-6.

10 Sq 1117 2 Sq 42 (627 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	--	1526.8	1527.6	1528.7	--	1531.6	1534.3	--	1536.5	1535.8	1532.4	--
10		1526.9	1527.7	1528.8		1531.5	1534.4		1536.4	1535.7	1532.5	
20		1527.1	1527.9	1528.9		1531.7	1534.6		1536.5	1535.7	1532.6	
30		1527.3	1528.0	1529.0		1531.6	1534.7		1536.7	1535.8	1532.7	
50		1527.4	1528.3	1529.0		1530.5	1534.2		1536.8	1536.1	1532.6	
75		1526.9	1528.4	1528.5		1528.7	1532.4		1529.2	1535.6	1532.3	
100		1526.1	1527.8	1526.9		1526.7	1529.3		1526.3	1531.5	1528.4	
125		1525.6	1526.4	1524.2		1524.5	1526.2		1524.7	1529.3	1526.7	
150		1524.0	1523.9	1521.6		1522.2	1522.8		1523.2	1526.9	1525.2	
200		1517.4	1518.4	1514.9		1515.8	1515.5		1519.0	1520.8	1520.0	
250		1508.9	1510.7	1507.3		1508.3	1507.9		1511.6	1512.9	1510.7	
300		1502.3	1503.6	1502.2		1501.8	--		1505.1	1505.7	1502.5	
400		1493.2	1493.7	1493.0		1492.5			1496.2	1494.5	1494.4	
500		1486.6	1486.3	1485.0		1486.0			1489.6	1487.7	1486.6	
600		1482.9	1482.6	1483.0		1483.3			1485.0	1483.4	1482.1	
700		1481.6	1481.4	1481.6		1482.2			1484.1	1483.2	1481.4	
800		1481.2	1481.5	1481.1		1481.6			1483.4	1483.2	1481.0	
900		1481.2	1481.9	--		1481.1			1483.1	1483.3	1481.6	
1000		--	1482.6			1482.0			1482.9	--	1482.3	
1100			1483.1			1482.8			--		1483.0	
1200			1483.9			1483.6					1483.7	
1300			1484.5			1484.4					1484.5	
1400			--			1485.2					1485.3	
1500						1486.1					1486.2	
1750						--					1488.8	
2000											1491.7	
2500											1498.8	
3000											1506.6	
4000											--	
No. of Surface Values	0	2	4	2	0	4	1	0	2	1	2	0

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Table V-7.

10 Sq 1117 2 Sq 40 (793 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1529.0	1526.5	1528.0	1528.1	1529.6	1531.2	1532.8	1534.9	1535.1	1534.4	1532.2	1531.4
10	1529.4	1526.7	1528.0	1528.3	1529.8	1531.3	1533.0	1534.3	1535.3	1534.5	1532.4	1531.6
20	1529.3	1526.9	1528.2	1528.2	1529.5	1531.0	1532.2	1534.2	1535.3	1534.7	1532.5	1531.6
30	1529.3	1527.0	1528.4	1528.1	1529.1	1530.6	1531.4	1534.1	1535.0	1534.8	1532.6	1531.6
50	1529.3	1527.2	1528.5	1527.9	1528.3	1529.0	1530.1	1533.8	1533.2	1535.1	1532.7	1531.7
75	1529.4	1527.2	1528.5	1526.8	1526.9	1527.5	1527.8	1531.4	1528.8	1531.7	1528.9	1531.7
100	1527.8	1526.5	1527.8	1526.1	1525.2	1525.7	1526.4	1528.8	1526.5	1527.8	1525.7	1528.0
125	1525.7	1524.5	1525.4	1525.0	1523.8	1523.3	1526.1	1527.3	1525.0	1525.3	1523.4	1526.3
150	1525.0	1521.7	1523.0	1523.2	1521.9	1520.8	1524.3	1524.8	1523.1	1523.0	1521.6	1523.9
200	1517.8	1514.8	1516.0	1515.5	1516.8	1513.9	1517.1	1516.7	1517.0	1516.1	1515.0	1516.9
250	1510.4	1506.5	1508.4	1507.3	1508.4	1506.5	1507.5	1509.4	1508.2	1507.8	1507.3	1508.5
300	1502.3	1499.6	1501.1	1501.2	1502.1	1500.9	1500.6	1502.9	1501.5	1500.8	1500.8	1500.5
400	1492.4	1490.3	1492.2	1492.0	1492.3	1492.4	1490.3	1493.4	1492.7	1491.9	1492.7	1492.6
500	1485.5	1483.6	1485.2	1485.0	1484.7	1485.6	1484.4	1486.7	1486.0	1485.2	1485.0	1485.4
600	1481.7	1481.0	1482.0	1481.7	1481.2	1482.2	1481.0	1482.7	1481.7	1481.3	1481.7	1481.6
700	1480.9	1480.8	1480.9	1480.9	1480.5	1481.4	1480.8	1482.1	1481.0	1481.3	1481.0	1480.8
800	1480.8	1480.9	1480.8	1480.7	1480.5	1481.1	1481.0	1482.1	1480.8	1481.3	1480.8	1480.7
900	1481.9	1481.4	1481.2	1481.1	1481.4	1481.5	1481.8	1482.2	1481.0	1481.7	1481.6	1481.6
1000	1482.8	1482.3	1482.1	1482.1	1482.2	1481.8	1482.5	--	1481.5	1482.3	1482.5	1482.4
1100	1483.3	1482.9	1482.8	1482.7	1482.8	1482.7	1483.0		1482.1	1482.5	1483.2	1483.1
1200	1483.8	1483.5	1483.4	1483.4	1483.6	1483.5	1483.6		1482.9	1483.4	1484.0	1483.9
1300	1484.4	1484.2	1484.1	1484.3	1484.4	1484.3	1484.3		--	1484.2	1484.8	1484.7
1400	1485.2	1485.1	1485.0	1485.1	1485.2	1485.5	1485.2		--	1485.0	1485.6	1485.5
1500	1486.0	--	1485.8	1486.1	1486.4	1486.0	--		1485.6	1485.9	1486.5	1486.4
1750	1488.7	--	1488.5	1488.6	1488.8	1488.6			1488.3	1488.5	1488.6	1488.9
2000	1491.7	--	1491.5	1491.6	1491.7	1491.7			1491.3	1491.5	1491.6	1491.8
2500	1498.8	1498.4	1498.4	1498.6	1498.9	1498.8			1498.4	1498.6	1498.6	1498.8
3000	1506.6	1506.5	1506.5	1506.5	1506.8	1506.7			1506.3	1506.5	1506.6	1506.6
4000	1523.7	1523.7	1523.7	1523.6	1523.7	1523.7			1523.6	--	1523.8	1523.7
5000	--	--	--	1541.5	--	1541.7			1541.6		--	--
No. of Surface Values	1	3	5	5	2	8	2	2	4	3	3	1

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Table V-8.

10 Sq 1116 2 Sq 68 (1080 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	--	1524.7	1525.4	1526.3	1528.0	1529.8	--	--	1535.2	1533.7	1529.9	1528.6
10	--	1524.6	1525.7	1526.0	1528.1	1530.0			1535.2	1533.8	1530.0	1528.7
20	--	1524.7	1525.8	1525.7	1527.8	1530.0			1534.9	1533.6	1530.0	1528.8
30	--	1524.9	1525.9	1525.5	1527.6	1529.8			1534.6	1533.2	1529.8	1528.9
50	--	1525.2	1525.8	1525.4	1527.1	1528.2			1532.2	1532.0	1529.3	1529.1
75	--	1525.5	1525.2	1525.7	1525.4	1526.5			1528.3	1528.1	1524.3	1529.3
100	--	1525.9	1524.1	1525.3	1524.9	1525.1			1526.3	1525.7	1522.2	1528.3
125	--	1524.3	1522.6	1523.3	1524.0	1522.8			1524.8	1523.2	1519.8	1524.4
150	1520.0	1521.0	1521.4	1520.8	1521.6	1520.2			1522.6	1519.2	1516.8	1521.4
200	1512.0	1514.5	1514.2	1513.9	1512.7	1513.0			1515.2	1511.5	1508.2	1512.1
250	1504.7	1505.5	1507.5	1506.6	1505.1	1502.8			1507.7	1504.9	1502.1	1504.1
300	1499.6	1498.9	1500.0	1500.6	1499.9	1498.5			1502.1	1500.1	1497.9	1500.0
400	1493.1	1491.8	1492.6	1492.6	1492.3	1489.3			1493.3	1492.7	1490.5	1493.4
500	1486.4	1485.0	1485.4	1486.0	1485.3	1483.8			1486.1	1485.9	1484.8	1486.3
600	1482.0	1481.6	1481.9	1482.0	1482.1	1481.7			1481.3	1481.7	1481.3	1481.3
700	1480.5	1481.0	1480.6	1480.9	1480.6	1480.6			1480.6	1481.1	1481.0	1480.3
800	1480.0	1480.7	1480.5	1480.6	1480.0	1480.4			1480.6	1480.9	1480.7	--
900	1480.5	1481.3	1480.9	1481.0	1480.7	1480.9			1481.2	1481.2	1481.2	--
1000	1481.3	1481.9	1481.5	1481.6	1481.4	1481.8			1481.6	1481.5	1481.8	--
1100	1482.3	1482.6	1482.4	1482.3	1482.1	1482.7			--	1482.4	1482.4	--
1200	1483.2	1483.4	1483.3	1483.1	1483.0	1483.6				1483.3	1483.1	--
1300	1484.1	1484.2	1484.2	1483.9	1483.8	1484.5				1484.2	1484.1	1484.0
1400	1485.0	1485.1	1485.2	1484.8	1484.7	1485.3				1485.0	1485.1	1484.9
1500	1485.9	1486.1	1485.7	1485.4	1485.8	--				--	1486.1	1485.8
1750	1488.4	--	--	--	--						1488.7	--
2000											1491.7	
2500											1498.6	
3000											1506.5	
4000											1523.7	
5000											--	
No. of Surface Values	1	2	3	2	3	3	0	0	3	2	2	1

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Table V-9.

10 Sq 1116 2 Sq 66 (1250 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1528.6	1522.7	1524.8	1525.4	1527.4	1529.6	1529.8	1532.8	1534.2	1533.1	1530.2	--
10	1528.8	1523.0	1524.9	1525.6	1527.4	1529.5	1530.0	1532.3	1533.9	1533.1	1530.3	
20	1528.9	1523.2	1525.0	1525.7	1527.4	1529.3	1529.3	1532.4	1534.1	1533.3	1530.5	
30	1528.9	1523.3	1525.2	1525.7	1527.5	1528.6	1528.7	1532.3	1533.2	1533.5	1530.6	
50	1529.1	1523.4	1525.5	1525.6	1527.0	1524.8	1527.7	1529.6	1528.3	1533.0	1531.0	
75	1529.2	1522.6	1526.0	1524.7	1526.3	1522.6	1524.8	1525.1	1524.8	1530.5	1531.0	
100	1529.4	1522.1	1526.4	1523.3	1525.1	1520.7	1524.1	1522.3	1523.1	1526.9	1525.7	
125	1525.9	1521.2	1526.8	1521.6	1523.6	1518.5	1523.7	1520.1	1521.9	1523.5	1523.5	
150	1523.9	1517.7	1526.8	1519.2	1521.6	1516.1	1523.7	1517.4	1519.9	1520.4	1521.0	
200	1518.0	1509.3	1518.2	1512.6	1515.2	1510.5	1519.7	1509.5	1512.7	1513.5	1513.5	
250	1509.0	1502.0	1508.2	1504.8	1508.3	1505.0	1511.7	1503.1	1504.5	1506.0	1505.8	
300	1499.3	1495.9	1500.4	1499.0	1501.9	1500.3	1503.9	1498.5	1499.0	1500.5	1499.1	
400	1493.1	1488.1	1492.8	1491.2	1492.5	1493.4	1495.8	1490.8	1490.9	1492.0	1490.3	
500	1486.3	1483.1	1486.2	1484.6	1486.0	1485.9	1488.4	1484.3	1483.6	1485.8	1483.9	
600	1482.0	--	1481.6	1481.3	1481.9	1482.6	1483.3	1480.8	1482.0	1482.8	1481.2	
700	1481.0	--	1480.6	1481.0	--	1482.0	1481.7	1480.5	1481.4	1482.0	--	
800	1480.7	--	1480.3	1480.8	--	1481.1	1481.1	1480.4	1481.1	1481.6	--	
900	1481.1	--	1480.8	1480.9	--	1481.5	1481.5	1480.6	1481.0	1481.4	--	
1000	1481.8	--	1481.5	--	--	--	1482.1	1481.3	--	--	--	
1100	1482.5	--	1482.3	--	--	--	1483.0	1482.2	--		--	
1200	1483.3	--		--	1482.9	--	1483.8	1483.1	--		--	
1300	1484.2	--		--	1483.8	--	1484.6	1484.0	--		--	
1400	1485.0	--		--	1484.8	1484.3	1485.3	--	1485.0		--	
1500	1485.9	--		1485.9	1485.8	1485.4	--	--	1485.9		--	
1750	--	1488.7		1488.6	1488.6	1488.1		1490.1	1488.5		--	
2000		1491.7		1491.5	1491.6	1491.3		1493.6	1491.5		1491.6	
2500		1498.6		1498.5	1498.5	1498.3		1498.6	1498.5		1498.4	
3000		1506.6		1506.4	1506.5	1506.4		1506.5	1506.5		1506.4	
4000		1523.7		1523.6	1523.6	1523.5		--	1523.7		1523.7	
5000		--		--	1541.7	--			--		--	
No. of Surface Values	1	2	1	5	3	5	2	3	3	2	2	0

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Table V-10.

10 Sq 1116 2 Sq 84 (1531 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	--	1519.8	1522.7	1523.2	1524.9	1527.2	--	--	1531.2	1532.1	1528.6	--
10	--	1520.1	1522.8	1523.3	1525.0	1527.1			1531.4	1532.2	1528.8	
20	--	1520.3	1523.0	1523.4	1525.2	1526.3			1531.4	1532.3	1528.9	
30	--	1520.4	1523.2	1523.3	1525.3	1525.7			1531.0	1532.5	1529.1	
50	--	1520.7	1522.6	1522.4	1525.7	1523.2			1526.6	1532.8	1528.9	
75	--	1521.1	1522.4	1522.5	1525.1	1521.3			1523.3	1526.3	1524.0	
100	--	1521.4	1521.8	1522.0	1525.2	1520.1			1521.8	1522.1	1521.0	
125	--	1521.1	1521.5	1520.7	1524.9	1518.6			1521.2	1519.4	1518.7	
150	1520.7	1519.3	1520.5	1518.9	1523.5	1516.5			1520.7	1516.4	1514.7	
200	1512.9	1510.4	1511.9	1514.2	1515.9	1509.6			1517.8	1509.5	1505.0	
250	1504.1	1503.1	1504.8	1504.8	1509.2	1502.8			1507.4	1503.9	1500.2	
300	1499.6	1497.5	1499.3?	1497.9	1503.2	1497.4			1499.6	1499.1	1496.0	
400	1491.4	1489.9	--	1490.2	1493.6	1490.1			1490.7	1492.4	1489.0	
500	1485.4	1483.0		1483.6	1487.0	1483.8			1483.7	1484.8	1483.1	
600	1482.3	1481.0		1481.1	1482.6?	1481.1			1481.1	1481.4?	1480.1	
700	1481.1	1481.0		1480.9	--	1481.0			1481.1	--	1480.2	
800	1480.8	1481.1		1480.9		1481.0			1481.3		1480.5	
900	1481.0	1481.4		1481.1		1481.2			1481.5		1480.9	
1000	1481.5	--		--		--			--		--	
1100	1482.1											
1200	--											
1300	--											
1400	--											
1500	--											
1750	--											
2000	--											
2500	1498.6											
3000	1506.4											
4000	1523.7											
5000	--											
No. of Surface Values	1	1	1	2	1	2	0	0	1	1	1	0

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Table V-11.

10 Sq 1116 2 Sq 82 (1701 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1520.2	1519.9	1521.2	1520.4	1523.3	1525.7	1532.1	1533.1	1532.6	1530.9	1526.7	1522.0
10	1520.4	1520.2	1521.3	1520.4	1523.3	1525.6	1532.0	1533.0	1532.8	1530.9	1526.8	1522.2
20	1520.5	1520.3	1521.4	1520.3	1523.2	1525.4	1530.5	1533.0	1532.9	1531.1	1526.0	1522.4
30	1520.7	1520.4	1521.6	1520.2	1523.2	1524.9	1528.8	1532.3	1532.7	1531.3	1526.3	1522.5
50	1521.0	1520.4	1522.0	1519.7	1523.1	1523.1	1525.6	1528.5	1529.0	1531.5	1526.1	1522.9
75	1521.6	1520.6	1522.2	1519.4	1521.6	1521.8	1522.8	1525.0	1523.7	1526.7	1520.8	1523.3
100	1521.6	1520.1	1521.7	1519.0	1518.7	1521.0	1520.6	1522.7	1521.0	1522.6	1518.9	1522.2
125	1518.7	1518.8	1519.3	1517.6	1515.8	1519.1	1517.8	1520.8	1519.2	1519.8	1518.0	1515.3
150	1514.6	1516.2	1516.7	1516.3	1512.9	1515.4	1513.8	1517.8	1515.8	1516.8	1515.6	1511.7
200	1504.1	1507.8	1507.1	1509.6	1505.4	1507.0	1504.9	1509.1	1506.6	1509.1	1507.9	1504.6
250	1498.0	1500.8	1500.6	1502.0	1500.6	1500.0	--	1503.0	1501.3	1502.8	1501.2	1498.7
300	1495.2	1496.4	1495.5	1496.7	1496.6	1495.1		1497.8	1497.7	1497.6	1496.2	1495.5
400	1489.9	1489.9	1488.4	1490.5	1489.0	1488.8		1490.5	1490.5	1489.2	1490.7	1488.7
500	1484.4	1484.3	1483.0	1484.0	1482.9	1483.7		1483.9	1483.8	1483.5	1484.4	1483.4
600	1480.4	1482.0	1479.7	1482.2	1480.4	1481.5		1480.8	1480.3	1480.7	1481.9	1480.4
700	1480.1	1481.4	1479.9	1481.1	--	1481.1		1480.6	1480.4	1480.4	1481.4	1480.2
800	1480.1	1481.1	4179.9	1480.9	--	1480.9		1480.8	1480.6	1480.4	1481.2	1480.6
900	1480.5	1481.0?	1480.3	--	--	1481.1		1481.1	1481.0	1480.7	1481.1	1481.1
1000	--	--	1480.8	--	--	1481.6		--	--	1481.3	--	1481.5
1100			1481.5	--	--	--		--	--	1482.0	--	1482.0
1200			--	--	--	--		--	--	1482.7	--	1482.7
1300			--	--	--	--		--	--	1483.5	--	1483.7
1400			--	--	--	1484.2		--	--	1484.4	--	1484.7
1500			--	--	--	1485.3		1485.6	1485.9	1485.6	--	1485.8
1750			1488.4	1488.3	1488.4	1486.5		1488.2	1488.3	1488.3	--	1488.5
2000			1491.4	1491.3	1491.5	1490.0		1491.3	1491.2	1491.4	1491.7	1491.4
2500			1498.6	1498.5	1498.6	1498.6		1498.5	1498.6	1498.5	1498.8	1498.4
3000			1506.5	1506.5	1506.5	1506.6		1506.5	1506.4	1506.5	1506.7	--
4000			1523.7	1523.6	1523.7	1523.6		1523.8	1523.7	1523.7	1523.8	
5000			--	--	--	--		--	--	--	--	
No. of Surface Values	1	4	3	3	2	4	1	3	3	3	2	1

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Table V-12.

10 Sq 1216 2 Sq 00 (1975 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1518.7	1517.1	1515.9	1517.6	1520.0	1524.3	1526.2	1528.8	1529.3	1528.3	1525.3	1522.5
10	1518.9	1517.2	1516.0	1517.6	1519.8	1524.1	1525.8	1528.5	1529.3	1528.4	1525.4	1522.6
20	1519.0	1517.3	1516.2	1517.7	1519.6	1523.3	1525.3	1527.6	1529.1	1528.6	1525.6	1522.8
30	1519.2	1517.5	1516.3	1517.8	1519.5	1522.6	1524.6	1526.5	1528.7	1528.7	1525.7	1522.9
50	1519.5	1517.7	1516.6	1518.0	1519.3	1520.9	1520.9	1521.0	1523.9	1525.9	1525.7	1523.3
75	1519.9	1518.1	1516.9	1518.1	1518.9	1519.8	1518.7	1517.6	1518.9	1519.8	1522.4	1523.0
100	1519.9	1518.3	1516.7	1517.5	1518.4	1518.4	1517.6	1516.2	1517.0	1517.8	1518.0	1520.3
125	1517.4	1516.7	1515.1	1515.4	1516.9	1516.7	1516.1	1514.7	1515.7	1516.2	1515.8	1517.3
150	1514.2	1513.3	1512.5	1512.5	1514.0	1514.0	1513.6	1512.3	1513.6	1513.6	1512.9	1514.2
200	1505.2	1504.3	1505.3	1504.9	1506.0	1506.2	1504.7	1504.4	1505.7	1504.9	1504.3	1505.8
250	1499.0	1498.6	1498.9	1499.4	1499.6	1499.9	1498.9	1498.5	1499.3	1498.5	1498.1	1499.4
300	1494.6	1494.4	1494.6	1495.0	1495.5	1495.4	1494.7	1494.1	1494.6	1494.1	1493.9	1494.7
400	1488.2	1487.9	1488.1	1488.4	1488.9	1488.9	1487.9	1487.8	1488.1	1487.7	1487.7	1488.3
500	1482.9	1482.8	1482.8	1482.8	1483.1	1483.2	1482.6	1482.7	1483.0	1482.9	1482.6	1483.2
600	1480.5	1480.4	1480.4	1480.3	1480.3	1480.4	1480.4	1480.4	1480.6	1480.6	1480.3	1480.6
700	1480.3	1480.2	1480.0	1480.0	1479.8	1480.1	1480.2	1480.1	1480.2	1480.2	1479.9	1480.1
800	1480.4	1480.3	1480.3	1480.1	1480.1	1480.2	1480.3	1480.3	1480.3	1480.2	1480.1	1480.3
900	1480.7	1480.7	1480.8	1480.5	1480.6	1480.6	1480.7	1480.7	1480.8	1480.7	1480.6	1480.7
1000	1481.4	1481.1	1481.4	1481.1	1481.3	1481.1	1481.1	1481.2	1481.3	1481.4	1481.2	1481.2
1100	1482.1	1482.1	1482.2	1482.0	1482.1	1481.9	--	1482.3	--	1482.4	1482.1	1482.1
1200	1483.0	1483.0	1483.0	1482.9	1482.9	1482.7	--	1483.1	--	1483.2	1483.0	1483.3
1300	1484.1	1483.8	1484.0	1483.7	1483.8	1483.7	--	1484.0	1483.4	1484.1	1483.9	1484.0
1400	1485.2	1484.7	1485.0	1484.6	1484.8	1484.7	1484.8	1484.8	--	1485.0	1484.8	1484.9
1500	1486.0	1485.6	1485.9	1485.7	1485.8	1485.6	1485.5	1485.7	1485.6	1485.9	1485.8	1485.7
1750	1488.5	1488.2	1488.3	1488.1	1488.3	1488.3	1488.4	1488.4	1488.5	1488.3	1488.5	1488.2
2000	1491.4	1491.4	1491.4	1491.2	1491.5	1491.4	1491.6	1491.4	1491.7	1491.3	1491.8	1491.3
2500	1498.6	1498.6	1498.6	1498.5	1498.6	1498.6	1498.6	1498.4	1498.6	1498.5	1499.0	1498.5
3000	1506.5	1506.5	1506.6	1506.4	1506.5	1506.6	1506.5	1506.4	1506.6	1506.5	1506.8	1506.5
4000	1523.8	1523.9	1523.7	1523.8	--	1523.7	1523.9	1523.7	1523.7	1523.7	1523.6	1523.7
5000	--	--	--	--		--	--	--	--	--	--	--
No. of Surface Values	62	54	60	67	99	86	69	76	109	101	67	60

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Table V-13.

10 Sq 1215 2 Sq 8 (2144 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1519.0	1517.5	1516.6	1517.2	1520.5	1525.1	1527.8	1529.9	1530.4	1528.8	1526.3	1522.2
10	1519.2	1517.5	1516.7	1517.2	1520.2	1524.9	1527.6	1529.7	1530.3	1528.8	1526.4	1522.3
20	1519.4	1517.6	1516.8	1517.3	1519.9	1523.7	1527.5	1529.4	1530.0	1529.0	1526.6	1522.5
30	1519.5	1517.7	1516.9	1517.4	1519.5	1522.6	1526.8	1528.7	1529.5	1529.0	1526.8	1522.6
50	1519.9	1517.9	1517.1	1517.7	1519.0	1520.2	1521.9	1523.6	1524.3	1526.4	1526.1	1523.0
75	1520.3	1518.1	1517.3	1517.6	1518.7	1519.0	1519.6	1519.8	1519.5	1520.5	1522.2	1522.9
100	1519.8	1518.1	1517.1	1517.4	1518.1	1517.9	1518.2	1518.1	1517.7	1518.2	1518.2	1519.9
125	1517.1	1516.3	1515.2	1515.3	1516.0	1516.2	1516.1	1516.5	1516.0	1516.1	1515.7	1516.8
150	1513.8	1512.9	1512.2	1512.4	1513.4	1513.6	1513.1	1513.9	1513.6	1513.3	1512.6	1513.5
200	1505.5	1504.0	1503.6	1505.3	1506.0	1505.8	1504.5	1505.2	1505.2	1505.0	1504.0	1506.1
250	1498.8	1498.1	1498.0	1499.5	1500.2	1499.9	1499.1	1498.8	1499.2	1499.0	1497.5	1499.6
300	1494.4	1493.8	1494.2	1494.9	1495.3	1495.4	1494.8	1494.4	1494.8	1494.6	1493.5	1495.5
400	1487.8	1487.4	1488.1	1488.4	1488.6	1488.7	1488.4	1488.0	1488.4	1488.0	1487.4	1488.9
500	1482.8	1482.5	1483.1	1483.1	1483.3	1483.3	1483.0	1482.8	1483.2	1482.9	1482.6	1483.3
600	1480.6	1480.2	1480.5	1480.6	1480.3	1480.5	1480.4	1480.4	1480.6	1480.4	1480.4	1480.6
700	1480.4	1480.0	1480.1	1480.3	1480.0	1480.3	1480.1	1480.1	1480.0	1479.8	1479.9	1480.0
800	1480.5	1480.1	1480.2	1480.5	1480.2	1480.4	1480.3	1480.2	1480.1	1480.1	1480.1	1480.3
900	1480.9	1480.6	1480.7	1480.9	1480.8	1480.8	1480.7	1480.7	1480.6	1480.6	1480.6	1480.9
1000	1481.4	1481.2	1481.3	1481.3	1481.6	1481.2	1481.3	1481.4	1481.1	1481.3	1481.3	1481.6
1100	1482.4	1482.1	1482.2	1482.7	1482.5	1482.0	--	1482.4	--	1482.3	1482.2	1482.3
1200	1483.2	1482.9	1483.0	1483.5	1483.3	1482.8	--	1483.2	--	1483.1	1483.0	1483.1
1300	1484.1	1484.1	1483.9	1484.0	1484.1	1483.6	--	1484.1	--	1483.9	1483.9	1484.0
1400	1485.0	1485.0	1484.9	1484.8	1485.0	1484.6	--	1484.9	--	1484.9	1484.9	1485.0
1500	1486.0	1486.0	1485.8	1485.8	1485.9	1485.7	1485.3	1485.8	--	1485.8	1485.8	1486.0
1750	1488.4	1488.3	1488.2	1488.3	1488.3	1488.7	1488.3	1488.4	1487.9	1488.3	1488.5	1488.6
2000	1491.4	1491.3	1491.3	1491.3	1491.4	1491.8	1491.4	1491.5	1491.0	1491.2	1491.6	1491.6
2500	1498.6	1498.6	1498.6	1498.6	1498.5	1498.9	1498.5	1498.5	1498.5	1498.4	1498.6	1498.6
3000	1506.6	1506.7	1506.5	1506.6	1506.5	1506.9	1506.4	1506.5	1506.4	1506.5	1506.6	1506.6
4000	1523.7	1523.9	1523.7	1524.0	1523.8	1523.8	1523.8	1523.7	1523.7	1523.8	1523.7	--
5000	--	--	--	--	--	--	--	--	--	--	--	
No. of Surface Values	51	52	70	38	59	55	51	48	59	55	45	33

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Table V-14.

10 Sq 1215 2 Sq 28 (2249 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1514.7	1511.5	1514.9	1512.2	--	1523.0	1520.9	--	--	--	1518.4	--
10	1514.9	1511.5	1515.5	1512.2		1521.6	1520.4				1518.4	
20	1515.2	1511.8	1515.7	1513.1		1515.0	1516.6				1518.3	
30	1515.2	1512.0	1515.8	1513.8		1510.5	1514.1				1518.1	
50	1515.7	1512.8	1515.6	1514.2		1508.1	1512.6				1513.3	
75	1514.8	1514.0	1515.9	1514.4		1507.7	1511.6				1510.0	
100	1513.6	1513.0	1516.3	1516.4		1504.6	1508.5				1508.4	
125	1511.2	1507.7	1512.8	1512.5		1504.7	1504.8				1507.1	
150	1506.8	1503.2	1510.3	1508.1		1503.2	1501.3				1503.2	
200	1497.0	1497.6	1507.4	1498.1		1497.8	1496.6				1495.2	
250	1493.4	1495.3	1504.5	1494.6		1495.1	1494.6				1493.3	
300	1491.5	1492.5	1501.4	1491.6		1492.0	1492.4				1490.9	
400	1486.2	1485.7	1494.9	1487.0		1485.9	1486.9				1484.7	
500	1482.9	1481.0	1487.2	1481.9		1481.4	1481.6				1480.8	
600	1479.9	1479.1?	1482.3	1479.1?		1479.5	1479.4				1478.9	
700	1479.9	--	1481.0	--		1479.7	1478.8				1478.6	
800	1480.1		1480.3			1480.1	1479.0				1479.1	
900	1480.6		1480.3			1480.5	--				1479.8	
1000	1481.1		1481.0			--					1480.8	
1100	1481.6		1488.2								1481.7	
1200	1482.6		1491.3								1482.3	
1300	1483.9		1498.5								--	
1400	1485.1		1506.6									
1500	1486.0		--									
1750	1488.1											
2000	1490.9											
2500	1498.5											
3000	--											
4000												
5000												
No. of Surface Values	1	1	2	1	0	1	1	0	0	0	1	0

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Table V-15.

10 Sq 1215 2 Sq 24 (2580 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt., to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1510.5	--	1512.1	1504.4	1511.9	1520.9	1520.5	--	1527.9	--	1522.6	1513.6
10	1510.8	1511.9	1510.3	1504.5	1511.9	1520.7	1520.7		1527.6		1522.9	1513.7
20	1511.1	1512.0	1509.5	1504.7	1511.2	1518.2	1520.0		1527.6		1523.0	1513.8
30	1511.2	1512.1	1509.1	1504.8	1510.8	1516.1	1519.3		1527.0		1523.2	1414.1
50	1511.4	1512.5	1509.6	1505.2	1510.6	1513.6	1514.2		1520.7		1517.8	1514.6
75	1512.1	1512.9	1510.4	1506.2	1510.6	1513.1	1511.4		1516.4		1514.9	1513.9
100	1511.3	1513.2	1512.3	1508.0	1511.1	1512.2	1510.5		1513.6		1511.7	1511.6
125	1507.2	1512.4	1509.5	--	1508.7	1509.4	1509.0		1511.5		1509.8	1508.8
150	1503.0	1511.4	1504.6		1505.3	1504.9	1506.4		1508.6		1506.0	1504.5
200	1496.1	1501.5	1495.6		1497.1	1498.4	1497.3		1500.0		1497.9	1496.4
250	1493.2	1495.4	1493.3		1494.0	1493.4	1493.1		1495.6		1493.9	1492.3
300	1490.2	1490.6	1490.7		1490.6	1490.1	1489.4		1492.0		1490.8	1488.8
400	1484.1	1485.5	1484.6		1484.4	1484.8	1483.9		1485.9		1485.0	1483.5
500	1480.9	1482.1	1480.8		1481.1	1481.0	1481.0		1481.4		1481.7	1481.1
600	1479.8	1480.3	1478.9?		1479.6	1480.1	1479.5		1479.9		1480.3	1480.1
700	1480.0	1479.8	--		1479.8	1479.9	1479.4		1479.7		1480.0	1480.0
800	1480.3	1480.5			1480.3	1479.8	1479.8		1480.1		1480.2	1480.3
900	1480.8	1481.1			1480.8	--	1480.5		1480.6		1480.6	1480.8
1000	1481.2	1481.5			--	--	1481.1		1481.3		1481.2	1481.4
1100	--	--				--	--		--		--	--
1200		--				--	--					
1300		--				1483.9	--					
1400		--				1484.8	--					
1500		1485.7				1485.7	1485.5					
1750		1488.5				1488.5	--					
2000		1491.6				--						
2500		1498.4										
3000		1506.3										
4000		--										
5000												
No. of Surface Values	5	1	3	1	4	4	4	0	7	0	4	3

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Table V-16.

10 Sq 1215 2 Sq 42 (2841 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	--	--	1503.0	--	--	--	--	--	--	--	1515.5	1514.3
10			1503.2								1515.0	1514.6
20			1503.3								1515.2	1515.7
30			1503.5								1515.3	1516.1
50			1504.1								1515.6	1516.5
75			1505.5								1506.4	1516.9
100			1503.2								1499.7	1500.5
125			1500.3								1496.5	1496.2
150			1497.4								1493.6	1492.8
200			1491.7								1489.5	1488.9
250			1489.2								1486.6	1487.0
300			1486.7								1484.8	1484.8
400			1481.9								1482.0	1481.3
500			1479.3								1480.6	1480.2
600			1479.1								1480.7	1480.7
700			1479.2								1480.2	1480.8
800			1479.9								1480.4	1480.8
900			1480.9								1480.5	1481.0
1000			1481.5								1481.0	1481.4
1100			1482.1								1481.7	1482.1
1200			1482.8								--	1483.0
1300			1483.6								--	1483.9
1400			1484.5								--	1484.7
1500			1485.3								--	1485.7
1750			1487.5								1488.1	1488.3
2000			1490.8								1491.3	1491.2
2500			1498.5								1498.5	--
3000			1506.6								1506.6	
4000			1523.9								1523.8	
5000			--								--	
No. of Surface Values	0	0	3	0	0	0	0	0	0	0	4	1

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Table V-17.

10 Sq 1215 2 Sq 40 (3007 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1505.3	1504.3	1504.1	1504.1	1508.3	1512.7	1513.8	1514.3	1519.3	1517.7	1514.2	1509.0
10	1505.5	1504.6	1504.0	1503.1	1508.0	1512.5	1513.6	1514.0	1518.8	1517.8	1514.1	1509.1
20	1505.6	1504.7	1503.7	1503.5	1507.5	1510.3	1513.3	1514.0	1518.6	1518.0	1514.2	1509.4
30	1506.0	1504.8	1503.5	1053.9	1506.5	1508.1	1512.7	1512.1	1518.0	1518.1	1514.4	1509.8
50	1506.5	1505.2	1503.3	1504.5	1505.1	1503.9	1508.2	1506.2	1513.2	1513.0	1509.7	1510.2
75	1505.6	1505.3	1504.8	1505.1	1504.5	1502.4	1504.7	1501.1	1505.2	1507.9	1500.1	1506.7
100	1501.5	1504.4	1503.4	1505.5	1504.2	1502.0	1502.8	1500.6	1501.4	1504.5	1496.0	1502.7
125	1497.2	1499.8	1499.7	1501.1	1500.4	1499.6	1499.3	1497.8	1498.7	1502.0	1494.4	1497.5
150	1494.2	1495.0	1495.7	1496.0	1496.2	1496.7	1495.7	1493.2	1495.0	1497.9	1492.2	1493.0
200	1489.8	1489.8	1490.0	1490.1	1491.9	1490.3	1490.1	1488.6	1490.2	1490.7	1488.4	1489.5
250	1487.8	1487.3	1487.2	1488.4	1488.5	1488.0	1487.6	1486.6	1487.8	1487.4	1486.1	1487.6
300	1485.4	1485.4	1484.8	1486.4	1486.1	1485.8	1485.3	1484.3	1485.5	1485.8	1483.8	1485.2
400	1481.5	1481.3	1481.3	1482.0	1481.6	1482.8	1481.3	1480.9	1482.0	1482.3	1480.7	1480.9
500	1479.7	1479.5	1479.7	1479.8	1479.9	1481.3	1479.6	1479.5	1480.2	1479.6	1479.4	1479.2
600	1479.1	1479.4	1479.6	1479.3	1479.0	1480.9	1479.2	1479.7	1479.8	1479.4	1479.0	1478.9
700	1479.5	1479.6	1480.3	1479.6	1479.2	1481.1	1479.3	1479.6	1479.7	--	1479.4	1479.3
800	1479.9	1480.0	1480.6	1480.0	1479.6	1481.2	1479.8	1479.7	1479.9		1480.1	1479.9
900	1480.6	1480.3	1481.0	1480.5	1480.2	1481.4	1480.4	1480.2	1480.4		1480.6	1480.4
1000	1481.1	1480.9	1481.3	1481.1	1480.8	--	1481.1	1480.9	1481.0		1481.1	1481.3
1100	1481.5	1481.7	1481.8	1481.8	1481.5	--	1481.6	1481.6	1481.9		--	1481.9
1200	1482.3	--	1482.5	1482.6	--	--	1482.5	1482.5	1482.7		--	1482.7
1300	1483.1	--	1483.3	--		--	1483.3	1483.4	1483.7		--	1483.5
1400	1484.0	--	1484.4			1484.6	1484.2	--	1484.7		1484.6	1484.5
1500	1485.3	--	--			1485.5	1485.5		1485.8		1485.7	1485.4
1750	1488.4	1488.3	1488.1			1488.1	1488.1		1488.4		1488.5	1488.1
2000	1491.5	1491.4	1491.1			1491.1	1491.2		1491.6		1491.5	1491.2
2500	1498.7	1498.6	1498.5			1498.7	1498.6		1498.7		1498.6	1498.6
3000	1506.7	1506.6	1506.7			1506.7	1506.5		1506.7		1506.6	1506.6
4000	1523.8	1524.0	1523.8			1523.8	--		1523.8		1523.8	1523.8
5000	--	--	--			--			--		--	--
No. of Surface Values	12	5	7	3	5	5	12	2	7	3	7	5

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Table V-18.

10 Sq 1214 2 Sq 48 (3175 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1503.6	1503.3	1501.2	1501.1	1503.7	1507.8	1511.4	1515.3	1516.5	1516.0	1515.6	1507.4
10	1503.8	1503.4	1500.5	1500.2	1503.3	1507.5	1511.5	1515.3	1516.4	1516.1	1515.8	1507.4
20	1504.2	1503.4	1500.2	1500.0	1502.4	1507.2	1511.2	1514.2	1515.6	1516.3	1515.9	1507.5
30	1504.4	1503.5	1499.9	1499.9	1501.0	1506.2	1510.2	1513.0	1514.5	1516.6	1516.0	1507.7
50	1504.8	1503.6	1499.1	1500.0	1498.7	1503.0	1505.6	1507.7	1510.6	1514.1	1513.7	1507.8
75	1504.4	1503.1	1498.0	1499.6	1497.6	1500.2	1501.8	1499.9	1501.9	1505.1	1506.0	1505.3
100	1499.6	1498.3	1496.1	1495.8	1496.4	1497.1	1498.1	1496.2	1498.0	1499.7	1501.2	1495.4
125	1495.3	1593.6	1492.5	1492.0	1492.8	1493.5	1494.8	1493.1	1494.0	1495.5	1496.3	1492.1
150	1492.1	1490.4	1489.8	1489.1	1489.8	1490.8	1492.2	1489.7	1491.0	1492.7	1492.5	1489.8
200	1488.3	1487.8	1487.4	1486.7	1487.2	1487.6	1488.4	1486.8	1487.7	1488.9	1488.4	1486.7
250	1486.5	1485.8	1485.7	1485.3	1485.5	1485.9	1486.6	1485.2	1485.9	1486.9	1486.4	1484.8
300	1484.4	1483.9	1484.2	1483.9	1483.6	1484.2	1484.8	1483.4	1484.3	1484.3	1484.3	1482.7
400	1481.2	1480.8	1481.5	1481.2	1480.6	1481.6	1482.5	1480.4	1481.4	1480.6	1480.7	1480.6
500	1479.9	1479.0	1480.3	1480.3	1479.8	1480.4	1481.2	1479.2	1480.1	1479.4?	1479.6	1480.1
600	1479.9	1478.9	1479.7	1480.5	1479.5	1479.9	1480.0	1479.0	1479.7	--	1479.2	1480.1
700	1480.2	1479.4	1479.8	1480.6	1479.6	1480.2	1479.9	1479.4	1479.9		1479.5	1480.3
800	1480.6	1479.9	1480.3	1480.7	1480.1	1480.7	1480.2	1479.8	1480.4		1480.1	1480.6
900	1481.1	1480.6	1480.9	1481.4	1480.6	1480.8	1480.7	1480.2	1480.9		1480.5	1481.3
1000	1481.6	1481.0	1481.3	1481.7	1481.2	1481.0	1481.2	1480.8	1481.3		1481.1	1482.0
1100	--	1481.6	1482.8	1482.3	1481.9	1481.5	1482.0	1481.6	1481.7		1481.8	1482.4
1200		1482.1	1483.4	1482.7	--	--	1483.2	1482.3	--		1482.7	1483.1
1300		--	1484.1	--			1484.0	1483.3			--	1484.1
1400			1485.0				1484.9	1484.4				1485.0
1500			1485.9				1485.8	--				1486.0
1750			1488.4				1488.1					1488.5
2000			1491.3				1491.2					1491.4
2500			--				1498.5					--
3000							1506.6					
4000							1523.8					
5000							--					
No. of Surface Values	13	7	7	7	8	6	12	4	10	3	6	4

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Table V-19.

10 Sq 1214 2 Sq 66 (3424 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1498.3	1497.2	1496.3	1497.0	1501.3	1502.1	1506.1	1510.2	1512.8	1511.8	1509.0	1499.5
10	1498.4	1497.3	1496.3	1496.5	1501.2	1502.2	1506.2	1508.6	1511.8	1511.9	1509.1	1498.9
20	1498.4	1497.4	1496.3	1496.5	1501.2	1502.3	1505.1	1505.5	1510.8	1511.7	1509.1	1498.9
30	1498.5	1497.6	1496.0	1496.1	1501.0	1501.7	1504.0	1503.4	1508.7	1511.5	1508.6	1498.7
50	1498.8	1497.7	1495.4	1495.1	1499.2	1498.9	1500.0	1497.1	1503.6	1503.2	1503.6	1497.1
75	1498.1	1494.5	1494.0	1493.7	1495.7	1493.3	1494.3	1490.8	1495.9	1494.4	1493.5	1490.1
100	1492.2	1490.4	1491.8	1490.5	1491.6	1489.1	1490.8	1487.5	1491.5	1490.2	1489.5	1488.2
125	1490.0	1489.4	1489.6	1488.0	1490.0	1486.6	1488.9	1485.5	1488.8	1488.2	1487.5	1486.7
150	1488.4	1488.4	1487.8	1486.3	1488.7	1485.7	1487.6	1484.3	1486.8	1486.4	1486.1	1486.0
200	1486.4	1486.9	1486.3	1484.4	1486.8	1484.7	1485.7	1483.9	1485.0	1484.5	1484.4	1485.1
250	1484.8	1485.5	1484.7	1483.0	1485.4	1483.3	1484.1	1482.6	1483.8	1483.0	1483.0	1483.3
300	1483.1	1484.4	1483.3	1481.5	1484.1	1482.1	1482.7	1480.4	1482.3	1481.3	1481.6	1481.8
400	1480.8	1482.5	1481.4	1479.6	1482.5	1480.2	1480.3	1479.0	1480.5	1479.7	1479.3	1479.6
500	1480.5	1481.4	1480.5	1479.0	1480.9	1479.4	1479.3	1478.9	1480.0	1478.8	1478.9	1478.1
600	1479.8	1480.2	1480.3	1479.0	1481.0	1479.3	1479.2	1479.4	1479.8	1479.3	1478.9	1478.1
700	1480.7	1480.3	1480.1	1479.5	1480.3	1479.7	1479.3	1479.7	1480.0	1479.7	1479.1	1478.9
800	1480.9	1480.7	1480.4	1480.0	1480.5	1480.3	1479.9	1480.0	1480.4	1480.1	1479.6	1479.7
900	1481.2	1481.1	1480.8	1480.5	1481.0	1480.8	1480.6	1480.1	1480.8	1480.3	1480.1	1480.5
1000	1481.7	1481.3	1481.4	1481.1	1481.6	1481.3	1481.4	--	1481.2	--	1480.9	--
1100	1482.4	1481.6	1482.1	1481.8	1482.2	1482.2	1482.1		1481.6		--	
1200	--	1482.2	1482.7	1482.6	1483.0	1482.8	1482.9		1482.1			
1300	--	--	1483.5	1483.5	1483.9	--	1483.8		1483.1			
1400	--		1484.3	1484.4	1484.7		1484.8		--			
1500	--		1485.3	1485.4	1485.7		--					
1750	1488.1		1488.0	1488.0	1488.2							
2000	--		1491.1	1491.1	1491.2							
2500			--	1498.7	1498.6							
3000				1506.7	1506.7							
4000				1523.8	1523.8							
5000				--	--							
No. of Surface Values	14	6	7	6	73	5	16	4	6	5	12	1

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Table V-20.

10 Sq 1214 2 Sq 64 (3590 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1495.6	1495.2	1495.3	1496.8	1499.7	1500.8	1504.2	1506.5	1512.9	1507.9	1503.8	1497.2
10	1495.6	1495.4	1495.2	1496.2	1498.0	1499.1	1503.5	1506.3	1511.8	1507.3	1503.7	1497.2
20	1495.5	1495.4	1495.0	1495.9	1497.4	1497.6	1501.9	1505.3	1510.4	1506.6	1502.8	1497.2
30	1495.4	1495.4	1494.3	1495.7	1496.0	1496.2	1499.9	1501.8	1507.5	1504.9	1501.0	1497.1
50	1494.7	1494.6	1492.4	1494.4	1494.1	1493.1	1493.7	1494.6	1499.3	1496.9	1495.3	1495.2
75	1491.3	1491.7	1490.0	1491.9	1490.6	1489.6	1490.0	1489.3	1493.8	1491.1	1490.2	1489.8
100	1488.3	1488.5	1487.6	1488.6	1487.8	1487.9	1487.8	1486.8	1492.1	1488.2	1487.2	1488.0
125	1486.8	1487.3	1486.2	1487.1	1486.7	1486.6	1486.4	1485.9	1491.1	1486.5	1486.1	1486.9
150	1486.0	1486.5	1485.2	1486.2	1486.0	1485.9	1485.3	1485.6	1489.9	1485.6	1485.2	1486.4
200	1484.5	1485.2	1483.9	1484.9	1484.7	1484.7	1484.1	1484.0	1487.4	1484.3	1483.9	1485.2
250	1483.1	1483.7	1482.3	1483.6	1483.2	1483.3	1482.7	1482.4	1485.5	1482.7	1482.7	1483.7
300	1481.9	1482.7	1480.9	1482.4	1482.1	1482.2	1481.7	1481.1	1483.7	1481.4	1481.5	1482.4
400	1480.3	1481.0	1479.4	1480.8	1480.4	1480.5	1480.2	1479.3	1481.3	1479.9	1479.8	1480.7
500	1479.6	1480.1	1479.0	1480.0	1479.6	1479.7	1479.5	1479.1	1480.0	1479.6	1479.7	1480.1
600	1479.5	1479.9	1479.3	1479.5	1479.8	1479.5	1479.3	1479.8	1479.6	1479.8	1479.8	1480.3
700	1480.0	1480.2	1479.7	1479.7	1480.0	1479.9	1479.4	1480.0	1479.8	1480.1	1480.1	1480.9
800	1480.4	1480.6	1480.1	1480.2	1480.4	1480.3	1480.0	1480.4	1480.2	1480.5	1480.4	1481.2
900	1480.8	1481.1	1480.6	1480.7	1480.8	1480.8	1480.5	1481.0	1480.7	1481.0	1480.9	1481.5
1000	1481.4	1481.4	1481.3	1481.3	1481.4	1481.4	1481.2	1481.6	1481.3	1481.5	1481.4	1481.9
1100	1481.8	1482.0	1482.1	1482.1	1482.2	1482.1	1482.0	1482.3	1481.9	1482.1	1482.1	--
1200	1482.5	1483.2	1482.8	1482.3	--	1483.1	1482.7	1483.0	1482.2	1482.5	1483.1	--
1300	1483.3	1483.9	1483.7	1483.2	--	1484.3	1483.6	1483.8	--	1483.5	1483.7	--
1400	1484.2	1484.7	1484.6	1484.2	--	1485.1	1484.6	1484.3		1484.4	1484.7	--
1500	1485.4	1485.8	1485.5	1485.2	--	1486.0	1485.6	1485.3		1485.3	--	--
1750	1488.3	1488.1	1488.1	1487.9	1488.4	1488.4	1488.0	1488.0		1488.1		1488.5
2000	1491.4	1491.2	1491.2	1491.1	1491.6	1491.5	1491.3	1491.1		1491.3		1491.5
2500	1498.8	1498.8	1498.8	1498.5	1498.9	--	1498.7	--		1498.5		1498.9
3000	1506.8	1506.8	1506.7	1506.7	1506.8		1506.7			1506.7		1507.0
4000	1524.0	--	--	1523.8	1523.8		--			1523.8		--
5000	--			--	--					--		
No. of Surface Values	45	20	16	34	22	23	51	11	18	21	31	6

Table V-21.

10 Sq 1214 2 Sq 62 (3736 km)
(Modified Canadian)

Historical Data, NODC Sound Speed Median Profiles, m/s; Makapuu Pt. to San Francisco

Depth	Month											
m	1	2	3	4	5	6	7	8	9	10	11	12
0	1495.7	1492.4	1493.3	1493.1	1494.4	1497.4	1500.5	1501.7	1504.6	1502.7	1499.1	1495.7
10	1495.8	1493.8	1493.0	1492.3	1492.8	1495.7	1498.4	1500.2	1502.3	1502.3	1499.5	1495.7
20	1496.0	1494.4	1492.5	1491.7	1490.6	1493.3	1495.6	1497.0	1500.6	1500.6	1498.7	1496.2
30	1495.9	1494.7	1492.2	1490.7	1489.0	1491.0	1493.2	1494.2	1498.1	1498.7	1497.4	1495.9
50	1494.6	1494.2	1491.2	1488.8	1487.3	1488.2	1490.1	1490.0	1493.5	1493.7	1493.9	1494.2
75	1491.9	1492.3	1489.2	1487.3	1486.1	1486.9	1488.0	1488.1	1491.3	1490.6	1490.8	1491.5
100	1489.6	1490.0	1487.7	1486.3	1485.7	1486.0	1486.8	1487.2	1490.4	1488.8	1489.4	1490.5
125	1488.4	1488.4	1486.9	1485.9	1485.3	1485.4	1486.2	1486.9	1489.7	1487.9	1488.7	1489.8
150	1487.6	1487.4	1486.4	1485.3	1484.8	1485.0	1485.8	1486.5	1489.1	1487.3	1487.9	1489.2
200	1486.3	1486.1	1485.5	1484.3	1483.9	1483.9	1484.8	1485.7	1487.5	1486.4	1486.7	1487.4
250	1485.0	1484.9	1484.5	1483.6	1483.3	1483.2	1483.9	1484.9	1486.0	1485.3	1485.6	1485.6
300	1483.9	1483.9	1483.5	1482.8	1482.8	1482.5	1483.2	1484.6	1484.9	1484.2	1484.2	1484.5
400	1482.4	1482.5	1482.3	1481.6	1481.9	1481.3	1481.9	1483.2	1483.0	1482.6	1482.5	1482.1
500	1481.4	1481.4	1481.3	1481.1	1481.1	1480.6	1481.1	1482.3	1481.6	1481.3	1481.2	1481.1
600	1480.8	1480.7	1481.0	1480.5	1480.7	1480.5	1481.0	1481.6	1480.9	1480.8	1480.5	1480.6
700	1480.6	1480.6	1480.7	1480.7	1480.7	1480.8	1481.0	1481.5	1480.7	1480.7	1480.6	1481.1
800	1480.8	1480.8	1480.9	1480.7	1480.9	1481.0	1481.3	1481.5	1480.8	1480.9	1481.0	1481.0
900	1481.3	1481.2	1481.3	1481.1	1481.2	1481.5	1481.6	1482.0	1481.1	1481.4	1481.3	1481.3
1000	1481.9	1481.7	1482.0	1481.7	1481.8	1482.0	1482.2	1482.3	1481.7	1482.0	1481.6	1481.8
1100	1482.6	1482.5	1482.4	1482.3	1482.5	1482.8	1482.9	1483.0	1482.4	1482.4	1482.3	--
1200	1483.3	--	1482.9	1483.1	1483.0	1483.3	1483.1	1483.3	1483.7	1482.7	1483.0	
1300	1484.1	--	1483.8	1484.0	1484.0	--	1483.2	--	--	1483.7	--	
1400	1484.9	--	1484.6	1484.8	--		1484.2		--	1484.5	--	
1500	1485.8	--	1485.5	1485.7	1485.8		1485.4		1485.5	1485.5	--	
1750	1488.4	--	1487.9	1488.4	1488.4		1488.2		1488.0	1488.0	1488.4	
2000	1491.5	--	1491.0	1491.3	1491.4		1491.3		1491.2	--	1491.6	
2500	1498.9	1498.7	--	1498.7	1498.8		1498.7		1498.7		1498.9	
3000	1507.0	1506.9		1506.8	--		1506.8		--		--	
4000	--	--		--			--					
No. of Surface Values	109	55	39	89	56	85	118	37	37	69	48	28

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V-5. References

V-1. "Sound speed profiles for the North Pacific Ocean," E.M. Podeszwa, NUSC Tech. Doc. 5271, February 1976, Naval Underwater Systems Center, Newport, Rhode Island.

General: Mrs. Rosa T. Washington, NODC, organized and provided the sound speed listings for the median profile data.

VI. SAMPLING OF TEMPERATURE FIELD

VI-1. An Example of a Vertical Temperature Cross Section from Oahu to San Francisco (Sampling Interval Along Path is 120 km)

There are many interesting features of this unique region for which oceanic time and length scales must be considered in determining the resolution of environmental detail that is required to understand and relate the environment to acoustic behavior. While it is a very complex region, it has been well studied. Ocean Weather Ship (OWS) NOVEMBER occupies a permanent station halfway along the path at 30°N 140°W. Also, the path lies along a major shipping lane, and since 1966 the National Marine Fisheries Service (NOAA) has conducted an extensive XBT measurements program with commercial ships of opportunity (Ref. VI-1). For about one week of every month, a ship plies between the two points, making XBT temperature drops down to about 460 m, along with surface temperature and salinity measurements every 4 hours.

Figure VI-1 shows an example of a vertical cross section of isotherms over this path, taken from Fishing Information (Ref. VI-2). It should be noted that the closeness of an acoustic path to a shipping lane is a mixed blessing since there will be more shipping noise to contend with than usual. The isotherms shown are used to study features that last much longer than the 5 or 6 days that it took to obtain the profiles. In the case at hand, the sampling interval is about once every 4 hours, or every 120 km if the ship is moving at 30 km/h (16 kn).

VI-2. A Vertical Temperature Cross Section from Oahu to San Francisco (Sampling Interval of 30 km)

A more detailed plot (Figure VI-2) can be made if an XBT is dropped once an hour for 5-1/2 days. At 30 km/h we get a sample spacing of 30 km. Obtaining XBT samples at this rate is quite taxing and becomes expensive. Also, at a ship's speed of 30 km/h, one is restricted to using a relatively shallow XBT, e.g., the T-4 which goes down to 460 m. It is possible to obtain XBT data down to 760 m (T-7) by slowing down somewhat to 27.8 km/h (15 kn). However, to obtain data down to 1830 m requires the use of the T-5 XBT at a speed of 11.1 km/h (6 kn). The T-5 is almost twice (1.8) as expensive as the T-7 and 2.2 times the cost of the T-4. Table VI-1 lists the available XBT probes, and their depth capabilities and cost.

VI-3. Accuracy and Resolution of XBT Probes

The temperature accuracy of the XBT probes is ±0.2°C with a depth accuracy of ±2% or 5 m, whichever is greater (Ref. VI-3). The temperature resolution is 0.1°C, and the time constant is 0.5 s. Thus, with a fall rate of 1 m/s the probes respond to a change in temperature in a layer of

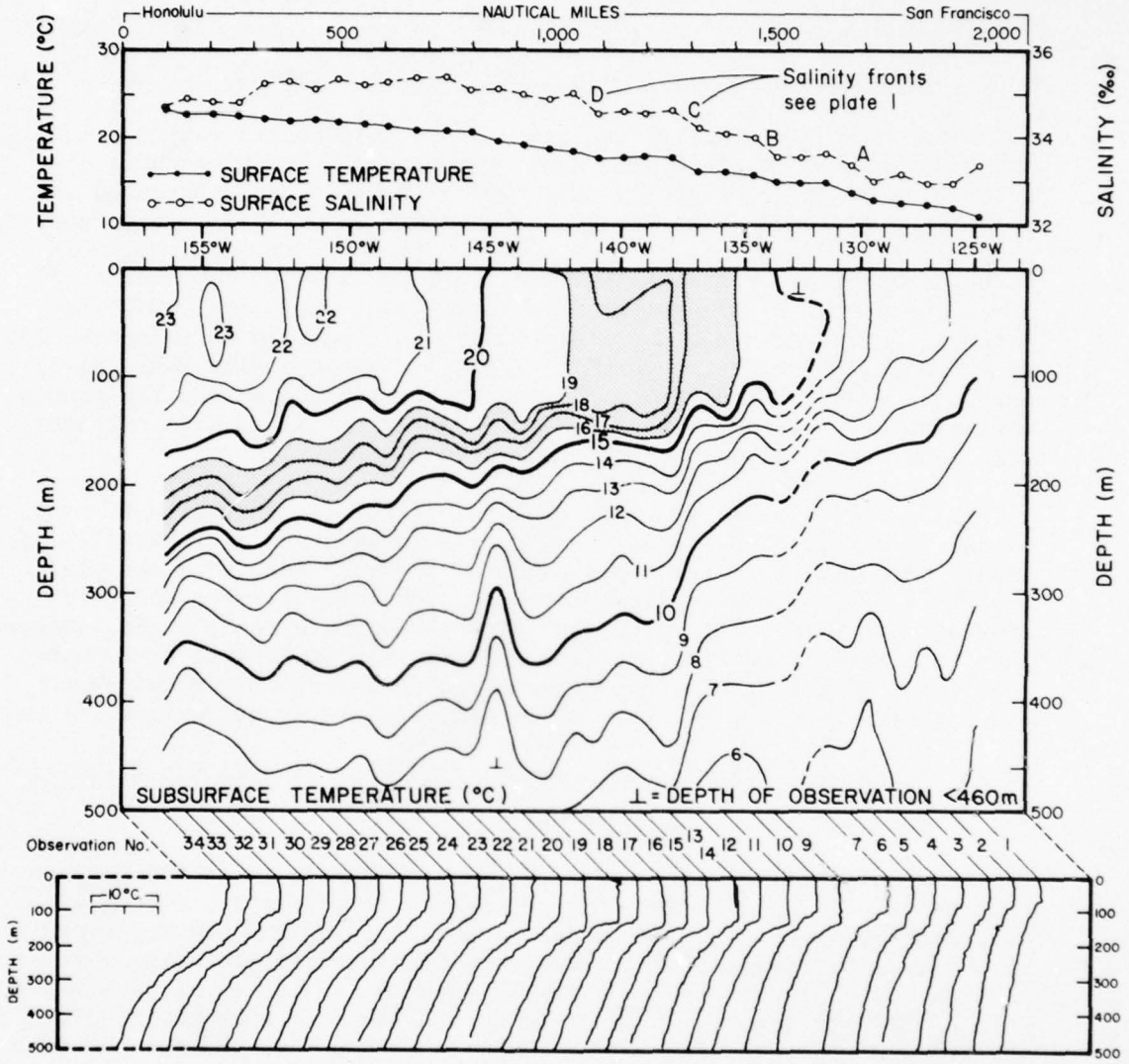

Figure VI-1. Honolulu to San Francisco, April 1-7, 1976, HAWAIIAN QUEEN, Voyage 178. (from Ref. VI-2)

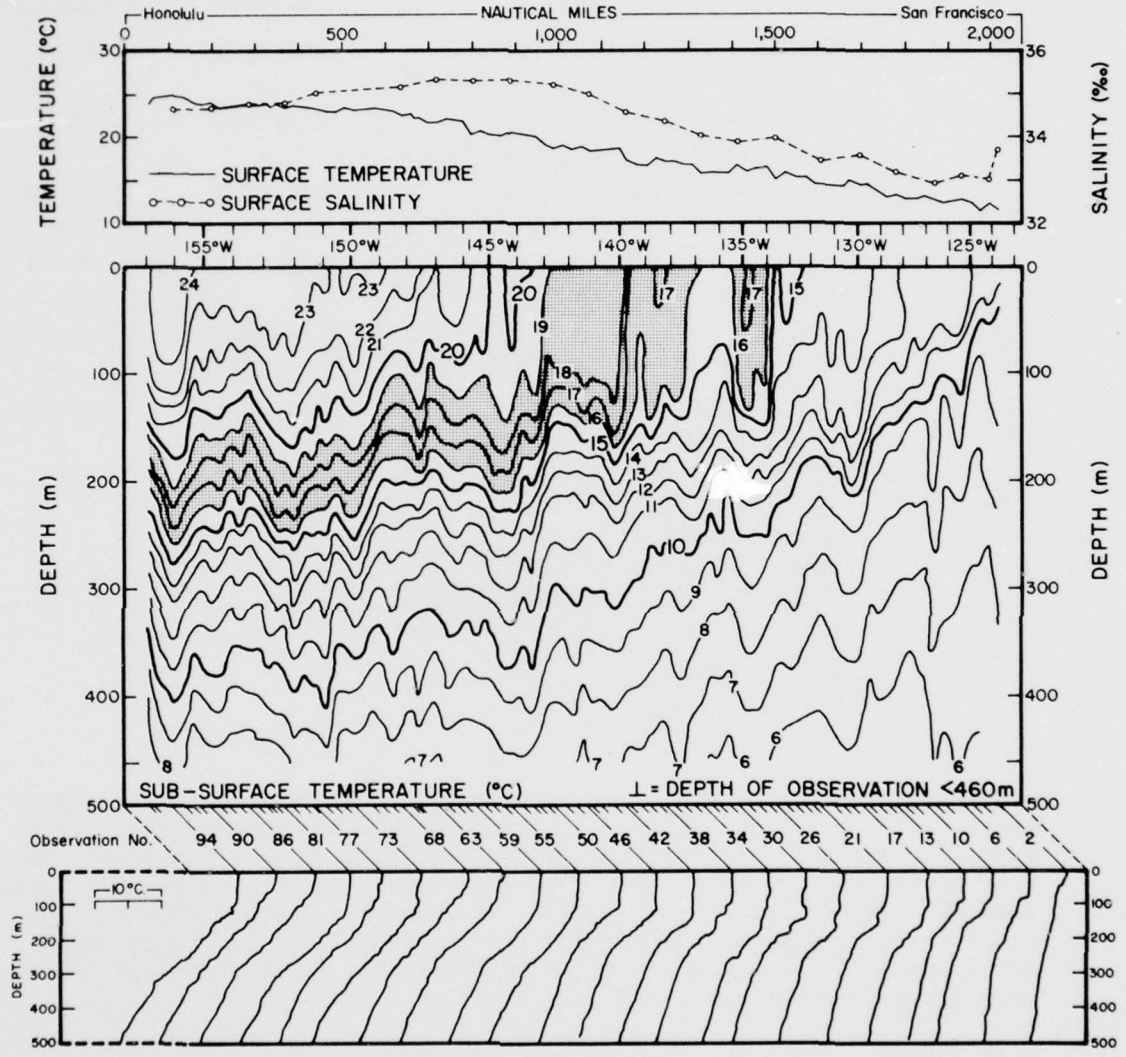

Figure VI-2. Honolulu to San Francisco, April 27-May 1, 1974, SS HAWAIIAN ENTERPRISE, Voyage 89. (from Ref. VI-7)

Table VI-1. XBT probes (The Sippican Corporation).

Model No.	Description	Part No.	Unit Price (8/1/78)
T-4	Depth - 460 m (1500 ft) Ship Speed - 30 kn (55.59 km/h)*	207592-1	$ 25.65
T-5	Depth - 1830 m (6000 ft) Ship Speed - 6 kn (11.12 km/h)	211105-1	56.85
T-6	Depth - 460 m (1500 ft) Ship Speed - 15 kn (24.09 km/h)	211965-1	21.30
T-7	Depth - 760 m (2500 ft) Ship Speed - 15 kn (27.80 km/h)	210883-1	30.90
T-10	Depth - 200 m (660 ft) Ship Speed - 10 kn (18.53 km/h)	213412-1	15.85
T-11	Finestructure (FSXBT) Depth - 460 m (1500 ft) Ship Speed - 6 kn (11.12 km/h)	213713-1	26.10
XSV-1	Expendable Sound Velocimeter Depth - 850 m (2790 ft) Ship Speed - 15 kn (27.80 km/h)	213796-1	66.00

*1 knot = 1.853 km/h = 0.5144 m/s

water of the order of 50 cm. Temperature error is due mostly to servomotor response in the recorder, the accuracy of the chart paper, and to a smaller degree, uncertainties in the thermistor calibrations and the wire resistance balance. The depth uncertainty is due to the individual launcher height, water entry conditions (surface wave height and probe entry angle) and probe fall rate. These uncertainties are well understood, and attempts have been made to limit them by special calibration procedures, digital recording, and the like.

VI-4. Improvements to Standard XBT Probe System

(a) XBT Digital Recorder and Display System

Scripps (SIO) has started to use a digital data logger designed by Dr. Mesecar at Oregon State University (Ref. VI-4). An analog-to-digital converter interfaces a PET microcomputer to a Sippican launcher and probe.

(b) Shipboard Environmental Acquisition System (SEAS)

This system is being developed and implemented by the National Weather Service. It has an XBT system with automated launching devised by Plessey Environmental Systems. The launching capability would be 1 XBT probe every 15 minutes, with the data being recorded automatically. Although the cost would be quite high, the sampling interval could be narrowed, in the extreme, to 7.5 km for a ship moving at 30 km/h.

(c) Expendable Sound Velocimeter (Sippican XSV)

A sing-around sound velocity sensor is used to measure sound speed to an accuracy of ±0.25 m/s down to 850 m. Together with a temperature probe, this device would be capable of measuring density vs depth directly.

VI-5. Merging of XBT Data with Historical Deep Data Records

There are many different procedures (e.g., Refs. VI-5,6) for merging depth-limited XBT data with historical deep ocean data records for a particular location. Where less than mesoscale sonar ranges (~100 km) are involved, the procedural details appear to have little effect. For mesoscale ranges, however, synoptic variability of the near surface isotherm depths may be forced on the historical data by improper extrapolation of shallow XBTs.

The NMFS program will use a technique that merges XBT and extrapolated surface salinity data together with historical, digital, deep ocean data files supplied by NAVOCEANO to enable computation of dynamic height (Ref. III-2) and sound speed profiles.

VI-6. Temperature Time Series vs Depth

It is highly desirable to obtain long-term time-series temperature variability data down to depths below the sound channel axis using thermistor arrays at a suitable location along the path. The use of a thermistor array (Refs. VI-8, 9, 10) could enable the study of the relationship of mesoscale time changes in the ocean to the propagation loss variability over the whole path. It will also give insight into interpreting the depth dependence of temperature fluctuations measured by the shallower XBT probes along the path.

As an example of the technique, deep ocean moored thermistor string buoys were used (Ref. VI-8) to study the temperature and sound-speed time-series vs depth for the Eleuthera-Bermuda acoustic path (1250 km). In addition to energy spectra for these fluctuations, vertical coherence was studied for isotherm displacements. Fluctuations of various scales were observed.

(a) Small scale fluctuations of generally less than 1 hour with 0.1°C to 0.2°C in amplitude. These have isotherm displacements of 10 m at all depths. The noise background was about 0.02°C with a measured time constant of 2 minutes.

(b) Semidiurnal (tidal) fluctuations, with displacements of 20 m to 50 m could be seen throughout the water column.

(c) Eddies with 3-day periods, a 1° to 2°C temperature range, and a displacement of 50 to 100 m separated by intervals of 12-13 days.

(d) Larger scale eddies were indicated but not resolvable by the 40-day record.

VI-7. References

VI-1. "Ships of opportunity: time-series expendable bathythermograph sections, Equatorial and North Pacific Ocean," Research Proposal for NSF(IDOE), D.R. McLain, P.N. Sund and F.T. Saur, NMFS Pacific Environmental Group, Summer 1976.

VI-2. Fishing Information, Ed. J.A. Renner, 4, (NOAA, Nat. Mar. Fish. Serv., Southeast Fisheries Center, La Jolla, CA, April 1976).

VI-3. "Subtle T4 XBT malfunction," J.P. Dugan and A.F. Schuetz, NRL Memo. Report 3612, September 1977, Naval Research Laboratory, Washington, D.C.

VI-4. "XBT digital recorder and display system specifications," R. Mesecar, Oregon State University, 1978.

VI-5. (a) "Evaluation of methods for merging BT-derived and deep climatological sound speeds," A. Fisher, Jr. and R. Pickett, NAVOCEANO Tech. Note 7700-12-73, 12 July 1973.

(b) "The ICAPS water mass history file," A. Fisher, Jr., N00 RP-19, May 1978, NAVOCEANO, Bay St. Louis, Mississippi.

VI-6. "Mesoscale variations in the deep sound channel and effects on sound propagation," W.J. Emery, T.J. Reid, J.A. DeSanto, R.N. Baer and J.P. Dugan (submitted for publication). [Supplied to author by Dr. Dugan]

VI-7. "Subsurface temperature structure in the Northeast Pacific Ocean," J.F.T. Saur, in Fishing Information, (NOAA, Nat. Mar. Fish. Serv., Southwest Fisheries Center, La Jolla, California, May 1974).

VI-8. "Environment variability in the deep sound channel," E.J. Softly and M.J. Engel, GE Doc. No. 77SDR2315, General Electric Co., Philadelphia, Pennsylvania, May 1977.

VI-9. "Constant depth ocean temperature and sound speed measurements over an eight day period southwest of Bermuda (August 1973)," Palisades SOFAR Station Report, May 1974.

VI-10. "Environmental and acoustic fluctuations in the sea," A.O. Sykes, Lecture on Ocean Acoustics, Catholic University of America, 22 June 1978.

General: Much of the information in Section VI has been derived from numerous personal communications with Dr. D.R. McLain, (NMFS). He arranged the provision of the "Fisheries" data and gave the author much assistance and consultation regarding the state of knowledge of XBT data and techniques. Dr. John P. Dugan (NRL) provided pertinent information on the limitations and use of XBT data. Mr. Alvan Fisher explained his water mass classification and merge technique. Mr. K.W. Lackie (NORDA) provided the information on Sippican XBT probes and the LRAPP experience with these probes.

VII. MESOSCALE ISOTHERM-DEPTH VARIABILITY

VII-1. Power Spectrum of 10°C Isotherm Depth Over Acoustic Path

How closely spaced must XBT drops be to resolve the time and length scales of importance to the acoustic problem? We saw earlier in Section V-1 that, according to Podeszwa's sound-speed profile classification, there are eight independent provinces along the path. These have an average length of about 480 km. Mesoscale features range from 100 km to upwards of 1000 km. If we wish to model these features for estimating their acoustic behavior, then the XBT spacing should be about 50 km or less. We can then determine the power spectrum of the variance of a mesoscale feature, e.g., 10°C isotherm depth, and find the distribution of energy density among the mesoscale wavelengths. In particular, the time and space behavior of the sound channel axis would be important for modeling purposes.

Dr. T. Davis has calculated for the author the spatial power spectrum (see Ref. VII-1) for the 10°C isotherm depth for a densely sampled (42.4 km) set of data taken over the Oahu to San Francisco path by Drs. R. Bernstein (Scripps) and C. Collins (NSF) in April 1974 (Ref. VII-2). (See Figure VI-2.) The power spectrum (m^2/cpkm) has been plotted against wavenumber, k, (cpkm) as well as wavelength (km) in Figure VII-1. This spectrum contains a number of bands for wavelengths less than 1000 km. Although the spectral slope is flat from 500 km to 2000 km, the envelope falls off generally as k^{-2}. The author has examined analysis techniques for the peaks shown in Figure VII-1. These peaks appear to be real and not the result of some artifact of the data analysis.

Wilson and Dugan (Ref. VII-3) made multiship XBT drops in two swaths south and north of the Kuroshio Extension in November 1975 (south) and May 1976 (north). The sampling data over the 1800 km long southern swath is shown in Figure VII-2a,b,c. The swath is 216-270 km wide and was covered by seven ships. The spacing between ships was about 45 km, while XBTs were dropped about every 27 km along the track. Figure VII-2a shows a plot of surface temperature for the swath with its cold and warm mesoscale features--in fact there are four cold intrusions. Figure VII-2b shows the same features in depth by contouring the depth of the 12°C isotherm which ranges between 250 m and 450 m. Figure VII-2c shows a vertical temperature section for one of the ships. Together, these figures present a three-dimensional view of mesoscale features, showing the relationship between surface and subsurface manifestations.

Figure VII-3, taken from the same study, shows the spectra for 10°C and/or 12°C isotherm depths for various latitudes. The spectrum for the less energetic southernmost latitudes, 29-30.5°N, resembles that of the Oahu-San Francisco path in both level and slope.

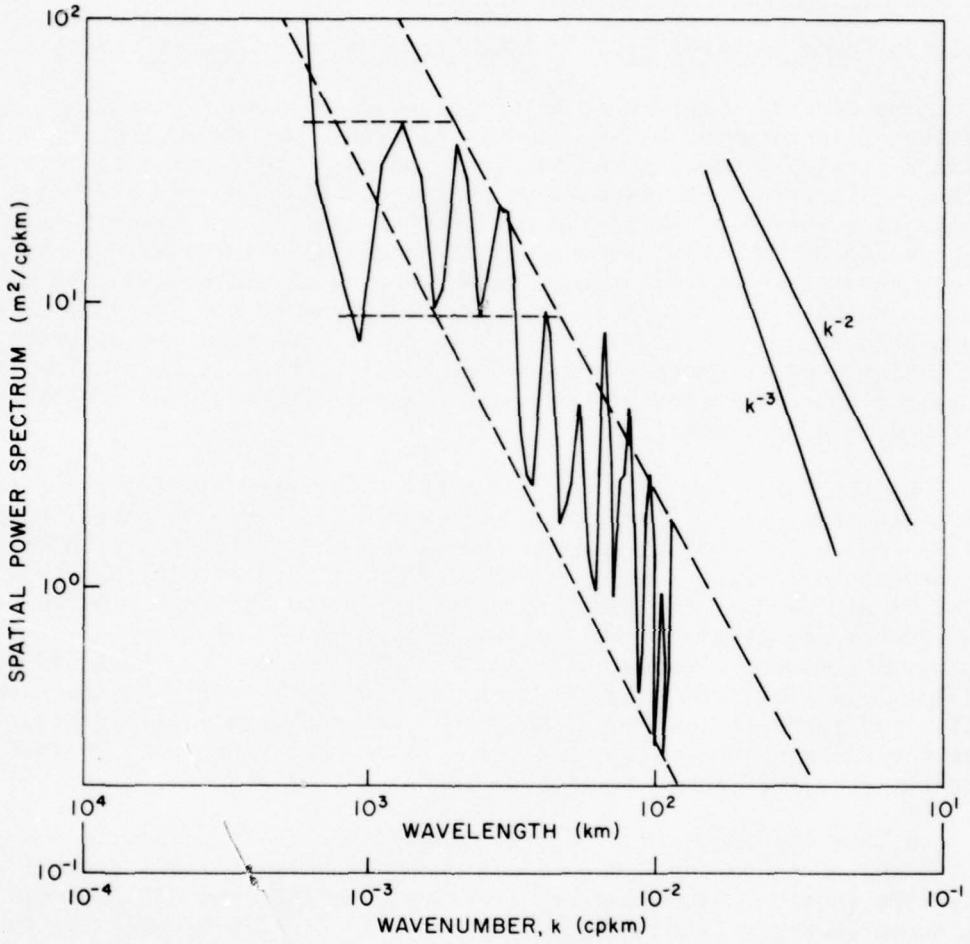

Figure VII-1. Power spectrum for 10°C isotherm depth, Oahu to San Francisco path; dense sampling (data interval of 42.4 km), April 1974.

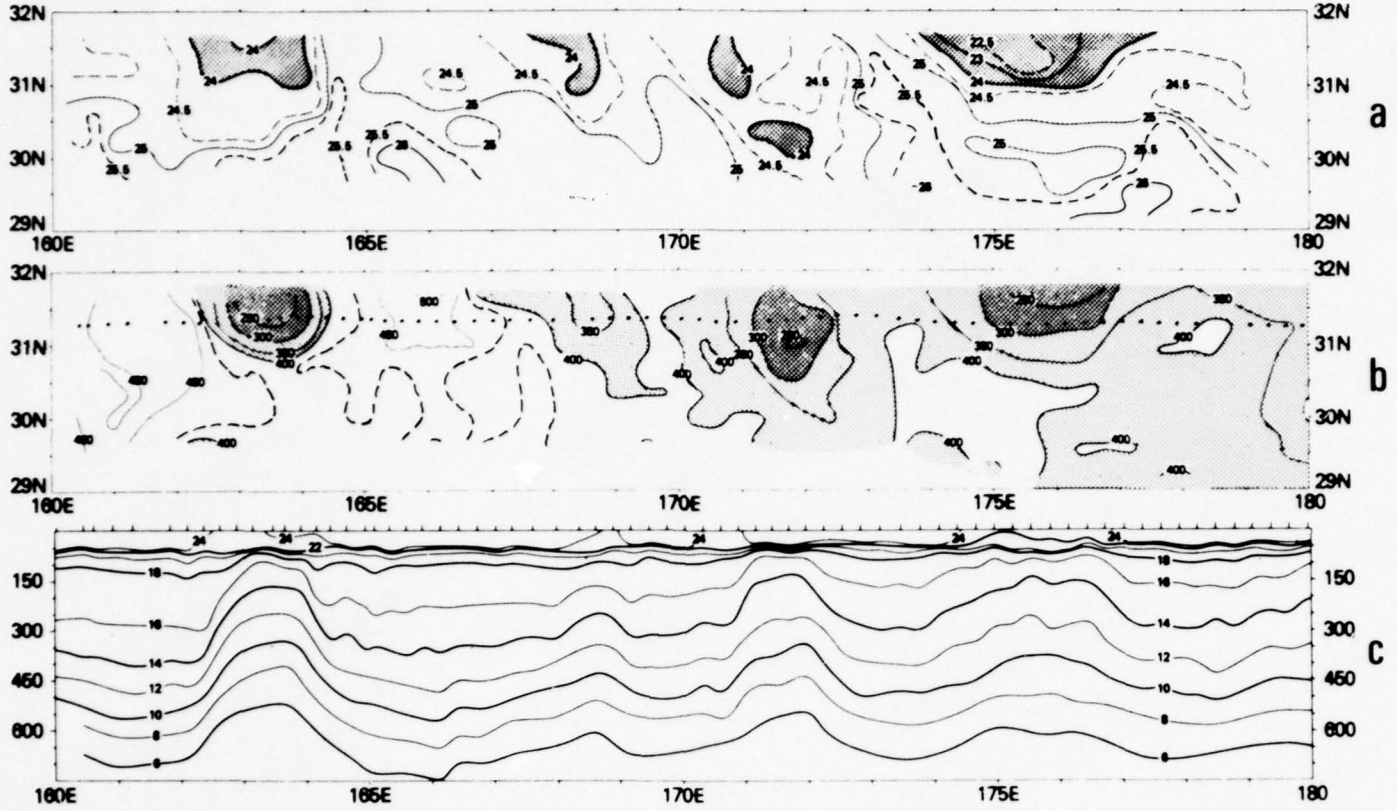

Figure VII-2. a--surface temperature in degrees Celsius; b--depth of the 12°C isotherm in meters; c--vertical temperature section, in degrees Celsius and meters, taken along the heavier dotted track in b above; data for a, b, and c were taken between 3 and 6 November 1975. (from Ref. VII-3; reproduced with permission)

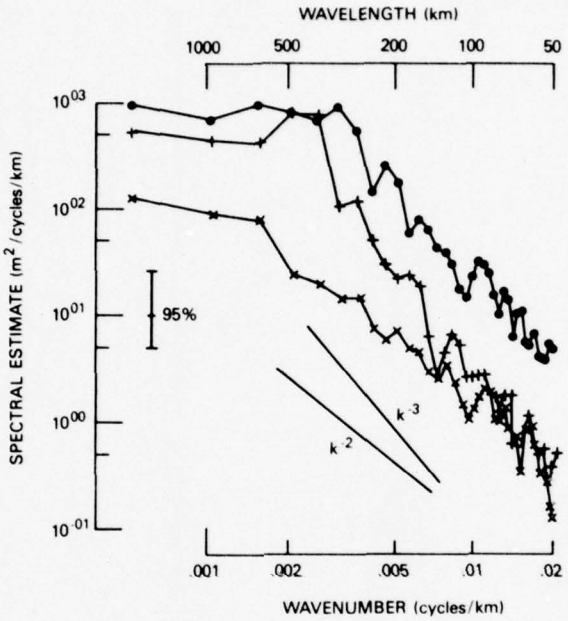

Figure VII-3. Spectra of isotherm displacement in main thermocline. (×) 12°C isotherm for three ships 29-30.5°N; (+) 12°C isotherm for three ships 30.5-32°N; (•) 10°C isotherm for six ships 36-38°N. (from Ref. VII-3; reproduced with permission)

Table VII-1 lists the power spectra computed for every second month for mid-1976 to mid-1977 for the standard NMFS XBT drop spacing of 120 km. The plots for these spectra are not included here, but they mostly show k^{-2} to k^{-3} dependence on wavenumber, k. However, they do not yield any data for mesoscale features below 240 km. There is also a larger mean square error of determining spectral amplitudes as will be discussed in the next section. Such spectra could be useful if there were more associated information. However, the recommended solution is to use closer spacing in the vicinity of fronts or sharp changes in temperature and salinity.

Table VII-1. Power spectra (m^2/cpkm) for 10°C isotherm depth, Oahu to San Francisco.

Wavenumber (cpkm)	Wavelength (km)	Bimonthly Series (Year 1976-1977) - 120 km Spacing						
		8/76	10/76	12/76	2/77	4/77	6/77	Median Set
2.60×10^{-4}	3840	103	118	157	156	146	2.56	60.68
3.91×10^{-4}	2560	94.9	133	7.2	22.7	19.4	5.65	7.42
5.21×10^{-4}	1920	28.7	1.96	1.2	10.9	4.65	1.51	4.15
6.15×10^{-4}	1536	22.2	3.68	9.87	6.20	2.25	2.39	3.32
7.81×10^{-4}	1280	15.7	1.37	6.82	4.36	1.39	5.87	1.71
9.11×10^{-4}	1097	11.8	1.47	8.65	5.19	2.49	10.2	2.65
1.04×10^{-3}	960	7.48	2.10	9.50	2.13	3.83	7.16	2.24
1.17×10^{-3}	853	4.36	1.53	4.47	1.23	2.67	2.42	0.772
1.30×10^{-3}	768	3.17	0.864	4.24	3.89	0.892	1.99	0.888
1.43×10^{-3}	698	2.48	0.698	6.66	6.71	0.722	4.94	1.13
1.56×10^{-3}	640	6.24	0.607	6.00	4.26	1.81	10.2	1.36
1.69×10^{-3}	591	9.73	0.571	5.15	2.07	2.16	10.1	1.91
1.82×10^{-3}	549	3.78	0.730	3.90	3.06	2.40	5.82	1.28
1.95×10^{-3}	512	0.672	1.12	1.77	3.58	5.17	4.80	0.303
2.08×10^{-3}	480	0.488	1.99	0.976	1.87	7.01	5.74	0.0333
2.21×10^{-3}	452	0.499	2.71	0.972	1.17	3.27	5.84	0.0153
2.34×10^{-3}	427	0.304	1.97	1.00	0.874	1.03	4.74	0.0677
2.47×10^{-3}	404	0.242	0.759	1.61	1.04	1.03	3.62	0.137
2.60×10^{-3}	384	0.283	0.305	1.60	1.72	0.810	2.62	0.0780
2.73×10^{-3}	366	0.409	0.236	0.709	1.07	0.540	1.26	0.0470
2.86×10^{-3}	349	0.359	0.123	0.929	0.399	0.630	0.880	0.121
2.99×10^{-3}	334	0.296	0.0861	1.70	0.263	0.365	2.18	0.168
3.13×10^{-3}	320	0.833	0.213	1.55	0.141	0.245	4.38	0.134
3.26×10^{-3}	307	1.56	0.216	1.28	0.179	0.419	3.75	0.153
3.39×10^{-3}	295	1.11	0.200	0.977	0.334	0.342	2.19	0.110
3.52×10^{-3}	284	0.548	0.680	0.601	0.271	0.379	2.85	0.030
3.65×10^{-3}	274	0.359	1.48	0.426	0.288	1.01	4.40	0.00943
3.78×10^{-3}	265	0.248	1.49	0.204	0.750	1.08	4.43	0.0131
3.91×10^{-3}	256	0.156	0.956	0.0184	1.17	0.231	3.59	0.0594
4.04×10^{-3}	248	0.0506	0.580	0.131	0.236	0.103	2.39	0.162
4.17×10^{-3}	240	0.00465	0.457	0.115	0.0182	0.390	4.37	0.157
		36 pts	32 pts	34 pts	36 pts	34 pts	36 pts	

VII-2. Sampling Error in Vertical Displacement

Another necessary procedure is to find the sampling error in vertical amplitude (Ref. VII-1). This tests the significance of the measured isotherm fluctuation amplitudes for determining power spectra. From Table VII-2 we can only say that the rms error in vertical amplitude for 2-data-interval spacing, or 85 km, would be about 10 m with respect to the error for the 42.4 km spacing. The total rms error in vertical amplitude is the root mean square of the two errors. The absolute error cannot be determined from this data set.

Table VII-2. rms sampling errors for 10° isotherm depths (10 degrees of freedom)

XBT Sample -- Data Interval = 42.4 km

Sample Spacing	rms Error in Depth
42.4 km	0 (assumption)
84.8 km	9.5 m
127.2 km	12.2 m

XBT Sample -- Data Interval = 120 km

Sample Spacing	rms Error in Depth
120 km	0 (assumption)
240 km	16.4 m

Note: The 10°C isotherm depth was read to the nearest 2 m in vertical amplitude. This should be part of the calculated rms error. The National Marine Fisheries Service should be able to supply values to closer tolerance from the original listings.

For the same set, Dr. Saur (Scripps) has found that the amplitude of the wavelength oscillations between 360 and 720 km is between 40 and 80 m in height. Those values are significantly larger than the ~10 m error involved.

VII-3. Time Scale for Mesoscale Waves

If it takes 6 days to get a mesoscale "snapshot" of the path's isotherm structure, then we may not be able to separate effects of time scales of less than 12 days. It turns out that, theoretically, baroclinic Rossby waves of 400 km length have a period of 7.7 months at 30°N latitude. Bourke and Pfeiffer have found nonseasonal periods of 7-8 months for cold water surges across the Subtropical Front from a study of records at OWS NOVEMBER (Ref. VII-4). The records were taken between 1962 and 1970. Those authors believe that the nonseasonal cold water surges in the upper 250 m at the southern boundary of the Transition Zone are related to nondispersive baroclinic Rossby waves. For a discussion of baroclinic Rossby waves in the Central North Pacific, see Bernstein and White (Ref. VII-5) and Roden (Ref. VII-6).

Table VII-3 summarizes the current estimates of time and length scales for mesoscale waves.

Table VII-3. Typical time and length scales for mesoscale waves.

Horizontal	100 to 1000 km
Vertical (10° isotherm)	~100 m
Time	7 to 8 months (nonseasonal)

VII-4. Basin-Scale, or Macroscale, Waves

It should be noted that most of the energy over this path corresponds to an oceanic scale of the length of the path (3835 km) because the baroclinic trend is monotonic practically all the way across the path. This can be seen in Figure VII-4, where median isotherm depths are plotted for a year for 10°C, 15°C, and 20°C. The baroclinic displacement for the 10°C isotherm is about 300 m.

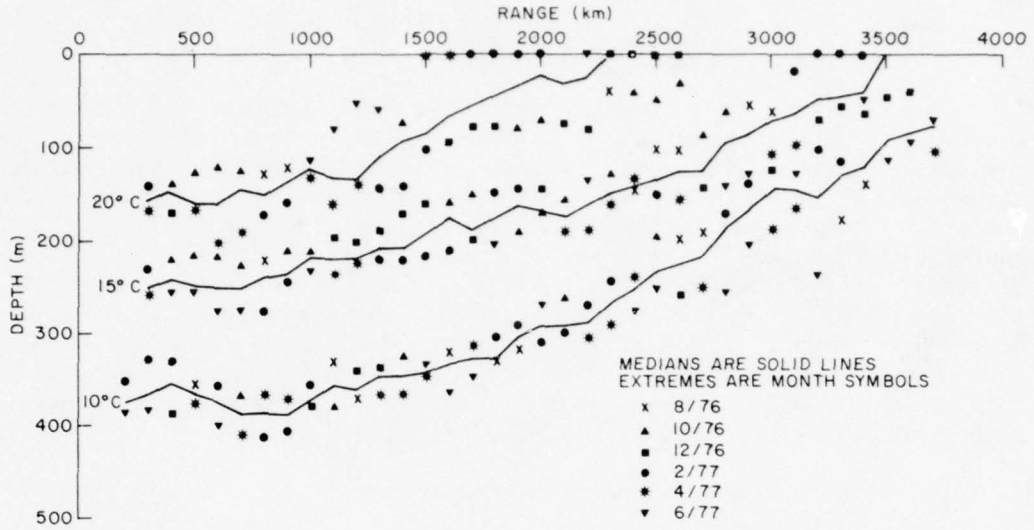

Figure VII-4. Depth variability ranges of major isotherms for Makapuu Point to San Francisco.

VII-5. Required Spacing and Depth of XBT Measurement

It would appear that if we use the NMFS ships-of-opportunity program, we must try to supplement it with: (1) XBT drops every hour (30 km spacing), or (2) at least use more frequent XBT drops in the water mass boundary regions where the largest changes occur.

When the Plessey automatic XBT launcher and recorder become available, then we may be able to increase our dense coverage data in an easier, but probably more expensive, manner. It would also be helpful to employ the 1830 m depth XBT, since its use does not require much slower ship speeds and since it covers the important vertical regions of change from baroclinicity to barotropicity near the sound channel axis. Wilson and Dugan (Ref. VII-3) used alternate 460 m and 760 m XBTs in their dense coverage of North Pacific swaths. However, in view of the necessity to follow the displacements of the sound channel axis, the use of 1830 m XBTs in some sequence, say one out of three, along with the others is almost mandatory. It is important to determine the interdependence of mesoscale vertical and horizontal displacements, and how these affect the sound speed profile (Ref. VII-7).

In Ref. VII-8, the use of analytical modeling and limited data for the modeling of mesoscale eddy properties is discussed. In Chapter VIII, we discuss satellite observations of surface temperature and/or dynamic height mesoscale patterns as additional information in relating the horizontal mesoscale features to the vertical displacement characteristics in the ocean.

VII-6. References

VII-1. "Theory and practice of geophysical survey design," T.M. Davis, NAVOCEANO RP-13, October 1974.

VII-2. "Subsurface temperature structure in the Northeast Pacific Ocean," J.F.T. Saur, in Fishing Information, (NOAA, Nat. Mar. Fish. Serv., Southwest Fisheries Center, La Jolla, California, May 1974), pp. 8,9.

VII-3. "Mesoscale thermal variability in the vicinity of the Kuroshio Extension," W.S. Wilson and J.P. Dugan, J. Phys. Oceanog. 8, 537-540 (1978). [Preliminary copy of data supplied by Dr. Wilson]

VII-4. "Evidence of subarctic water mass intrusions at ocean weather station NOVEMBER," R.H. Bourke and J.F. Pfeiffer, J. Geophys. Res. 83, 4561 4565 (1978). [Preliminary copy provided by Dr. Bourke]

VII-5. "Time and length scales of baroclinic eddies in the Central North Pacific Ocean," R.L. Bernstein and W.B. White, J. Phys. Oceanogr. 4, 613-624 (1974).

VII-6. "On long-wave disturbances of dynamic height in the North Pacific," G.I. Roden, J. Phys. Oceanogr. 7, 41-49 (1977).

VII-7. "Zonal variability in the distribution of eddy energy in the mid-latitude North Pacific Ocean," R.L. Bernstein and W.B. White, J. Phys. Oceanogr. 7, 123-126 (1976).

VII-8. "Use of analytical modeling and limited data for prediction of mesoscale eddy properties," R.F. Henrick, M.J. Jacobson and W.L. Siegmann, J. Phys. Oceanogr. 9, 65-78 (1979).

General: Dr. T.M. Davis (NAVOCEANO) supplied the author with the power spectra of isotherm-depth variability as well as much advice on the sampling problem.

VIII. SATELLITE COVERAGE OF AN OCEAN ACOUSTIC PATH

VIII-1. Satellite Oceanography

The use of satellites to monitor mesoscale features of the ocean surface on a continuous basis offers promise with regard to providing a predictive capability for underwater sound transmission over very long paths. The synoptic XBT data along paths like the Oahu to San Francisco path, and an understanding of the relationship between sea surface patterns and isothermal or isopycnal surface patterns at depth, should allow us to extend our range of coverage for modeling purposes. The required understanding can, of course, be provided by historical data as well as theories and models of ocean circulation.

Satellite areal coverage performance figures are given in Table VIII-1 for SEASAT-1 (now inoperational).

Table VIII-1. SEASAT-1 coverage.

Pass Period:	90 minutes
Spacing of Passes:	16 km
Repeat Coverage:	5 months
Time to Cover Honolulu to San Francisco Path:	14-15 days
Relative Dynamic Height Accuracy:	±10 cm

Table VIII-2, adapted from Reference VIII-1, presents one estimate of the required remote sensing accuracy, resolution, frequency of coverage, and extent of coverage of oceanographic parameters which could be of importance in modeling extremely long range acoustic paths.

Table VIII-3, also adapted from Reference VIII-1, provides an abbreviated list of remote sensing vehicles, their pertinent instrumentation for the parameters shown, the oceanographic application, and the sponsoring agency.

A useful data bank is supplied by the GOSST-COMPT program of NOAA-NESS at Camp Springs, MD. Global operational sea surface temperatures (GOSST) for 50 km x 50 km squares are stored for data starting six years ago. The temperature values are five-day averages.

Table VIII-2. Needed parameters for thermohaline models. (adapted from Ref. VIII-1)

PARAMETER	ACCURACY	RANGE OF VARIABLE	HORIZ. RESOL.	PERIOD	AREA SIZE
Relative Sea Surface Temperature	0.25°C 0.5°C	10°C 35°C	5 km 30 km	3 h 12 h	200 x 200 km Ocean Basin
Absolute Sea Surface Temperature	0.5°C 0.5°C	0-35°C 0-35°C	5 km 30 km	3 h 12 h	200 x 200 km Ocean Basin
Relative Surface Topography	3 cm 5 cm	1 m 2 m	5 km 30 km	24 h 72 h	200 x 200 km Ocean Basin
Absolute Wind Stress Vector	0.2 dynes/cm^2 0.25 dynes/cm^2	0-20 dynes/cm^2 0-20 dynes/cm^2	5 km 30 km	3 h/15° 12 h/45°	200 x 200 km Ocean Basin
Currents	cm/sec (10%) cm/sec (20%)	4-400 4-400	5 km 30 km	3 h/15° 12 h/45°	200 x 200 km Ocean Basin
Sea State Height	50 cm 50 cm	0-15 m 0-15 m	5 km 30 km	3 h 12 h	200 x 200 km Ocean Basin
Salinity	0.05 ‰ 0.1 ‰	0-40 ‰ 0-40 ‰	5 km 30 km	3 h 12 h	200 x 200 km Ocean Basin
Rain	1 mm/h 1 mm/h	1-100 mm/h 1-100 mm/h	5 km 30 km	3 h 12 h	200 x 200 km Ocean Basin

Table VIII-3. An abbreviated list of remote sensing vehicles. (adapted from Ref. VIII-1)

MODE	DATA	PARAMETER	APPLICATION	SOURCE
Aircraft	AXBT High + low altitude B & W photography Laser profile tapes Radiometric temperatures	Thermal profile reflectance, etc. Micro-altitude SST	Acoustics sea state (noise) Wave height (noise) currents, fronts	DOD
DMSP-5D	Visual and thermal photography and CCTs	Reflectance radiom. temp. (SST)	Currents, fronts, eddies	DNOM
NOAA-5	Visual and thermal photography and CCTs	Reflectance radiom. temp. (SST)	Currents, fronts, eddies	NESS
GEOS-3	Altimeter	Surface roughness Sat. altitude	Wave height (noise) Sea surf. topog. (currents, eddies)	NASA
NIMBUS	Infrared radiometer (11.5 μm and 6.7 μm)	SST, prec. moist.	Currents, fronts, etc.	NASA

Such information can be used in conjunction with the monthly sea surface temperature data provided by NMFS for the North Pacific (Ref. VIII-2). The contours shown in Figures VIII-1,2,3 are plotted from data acquired and stored at the Fleet Numerical Weather Central in Monterey, CA.

VIII-2. Mesoscale Dynamic Height Perturbations

The spatial distribution of dynamic height determines the configuration of the baroclinic flow field. This field consists of a mean flow and perturbations. The mean dynamic topography with respect to 1000 decibars is well known (Ref. VIII-3) and is shown in Figure VIII-4. The dominant features are the subtropical highs and the subpolar and equatorial lows, the position and extent of which vary with season and depth. Typical length scales of these features are several thousand kilometers. Table VIII-4 is a compilation of monthly data, provided by NODC (NOAA) for the Oahu to San Francisco path. These data are in good agreement with Figure VIII-4. (The NODC data is referenced to 1000 m/1500 m; 1 m is ≈1 decibar.)

Roden (Ref. VIII-4) finds that data from closely spaced stations about 30 km apart along a 2700 km path, with vertical sampling at 3 m intervals down to 1500 m, show perturbations superposed on the mean dynamic topography. Wavelike disturbances with length scales between 400 and 600 km and heights of the order of 10 dynamic centimeters are common in latitudes 20°N to 50°N. The wave amplitudes are larger in the western than in the central and eastern Pacific. This last observation is in agreement with Section VII of this report.

Roden finds further that the wavelike disturbances extend down to several hundred meters in depth with an exponential decrease in wave amplitude. Emery et al. (Ref. VIII-5) find significant mesoscale perturbations of the sound channel axis depth at about 800 to 900 m.

The baroclinic currents associated with the dynamic height perturbations are an order of magnitude larger than the mean currents and are related to the curl of the wind stress field. One inference from Ref. VIII-3 is that a time series analysis of the difference in sea level readings corrected for tides between Oahu and San Francisco should yield periods associated with the mesoscale dynamic height perturbations.

Table VIII-5 shows the contribution to dynamic height from 1500 m to 1000 m in dyn cm for the Oahu to San Francisco path. There does not appear to be a trend by month or distance for the small amount of data. The median contribution is 35 dyn cm.

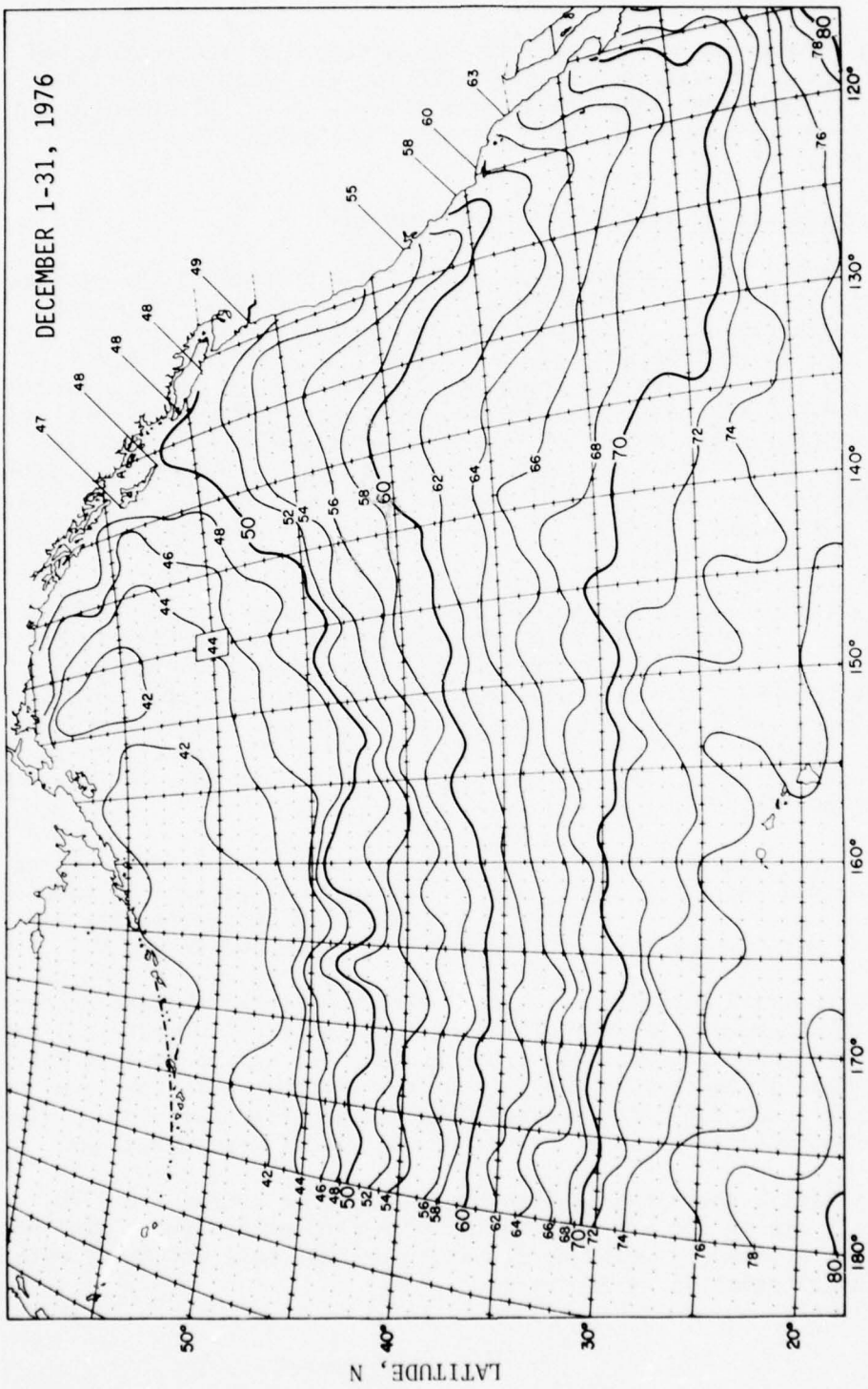

Figure VIII-1. Mean sea surface temperature (°F), eastern North Pacific Ocean. (from Ref. VIII-2)

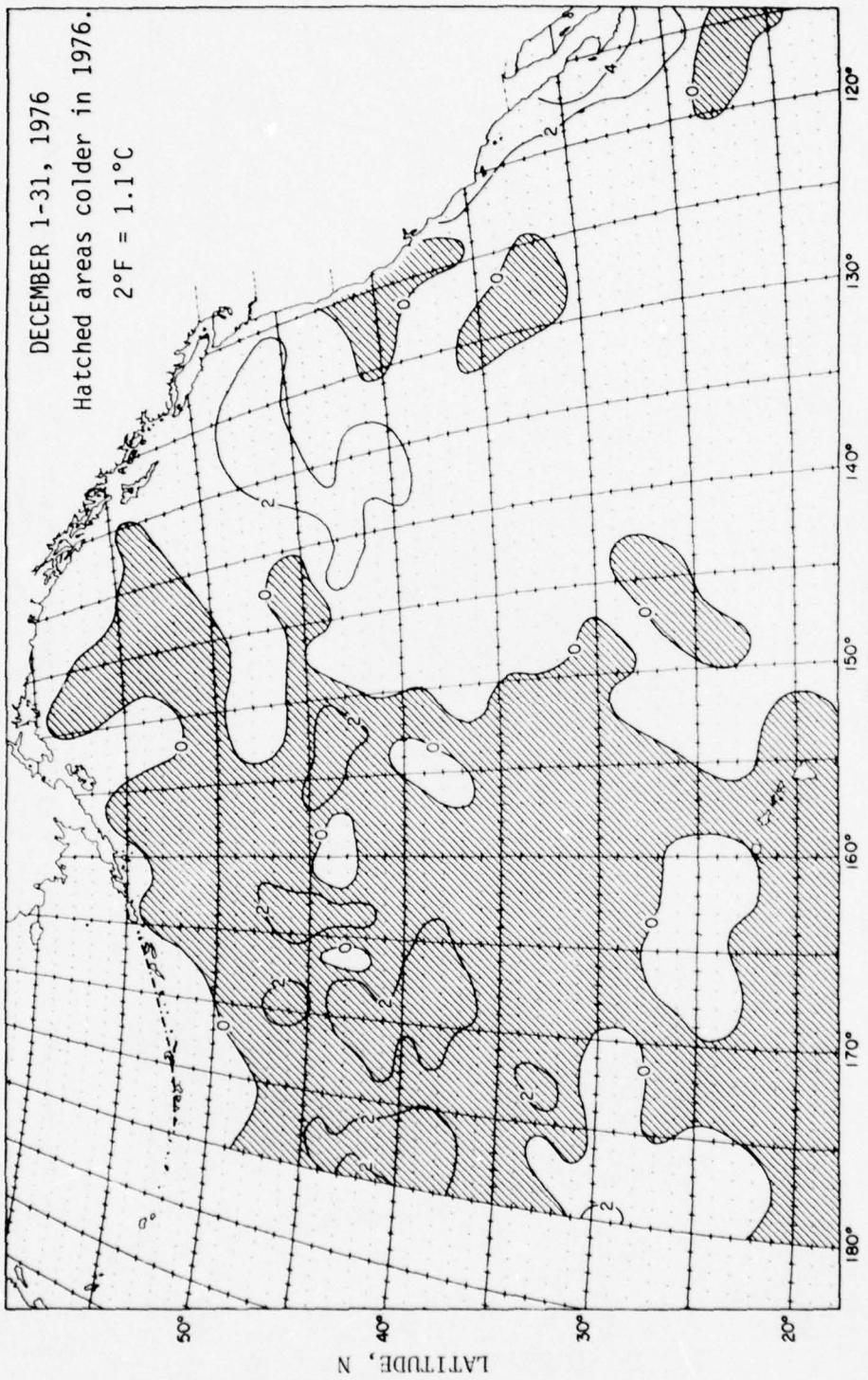

Figure VIII-2. Deviation of sea surface temperature (°F) from 20-year mean (1948-1967), eastern North Pacific Ocean. (from Ref. VIII-2)

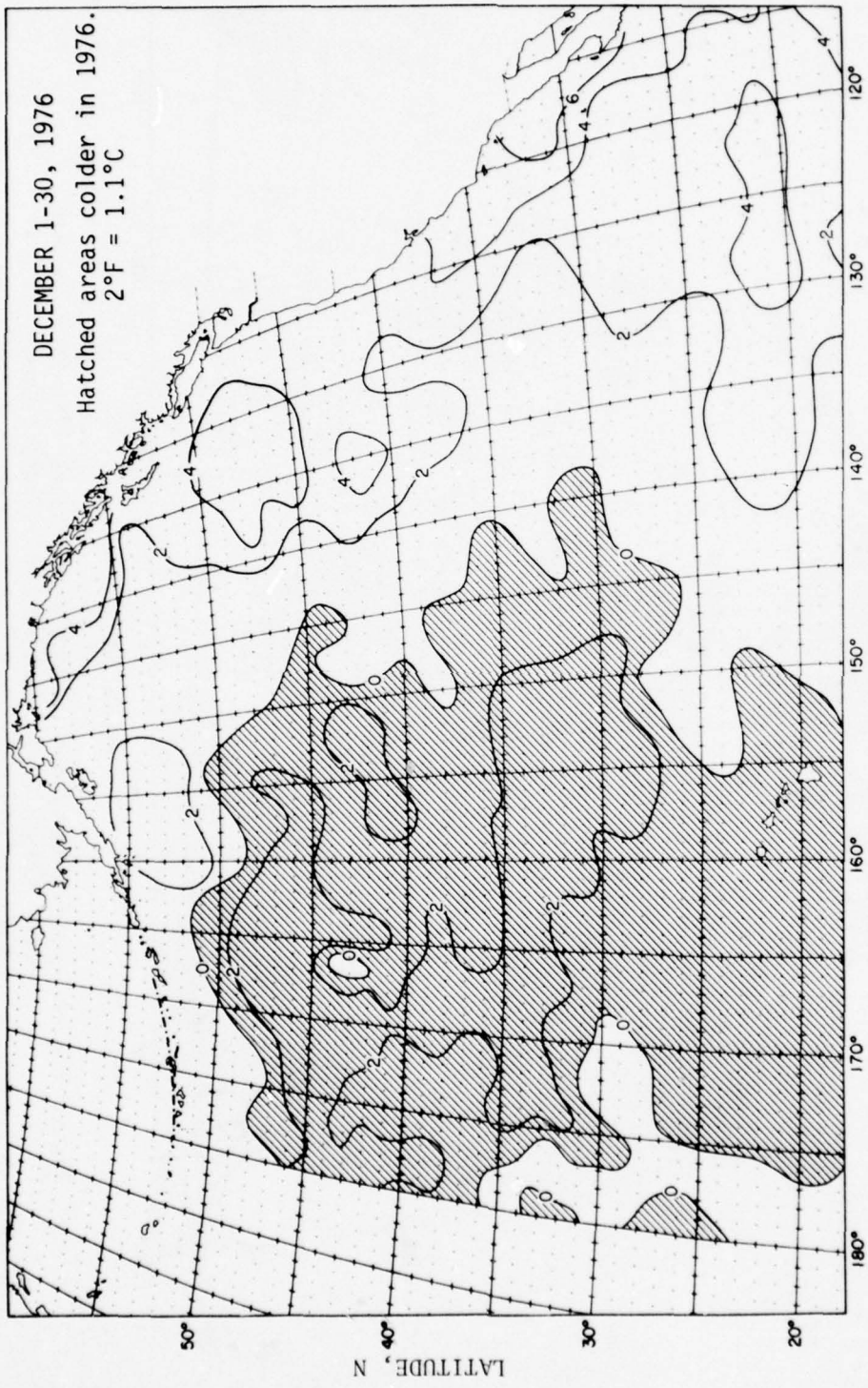

Figure VIII-3. Deviation of sea surface temperature (°F) from December 1975, eastern North Pacific Ocean. (from Ref. VIII-2)

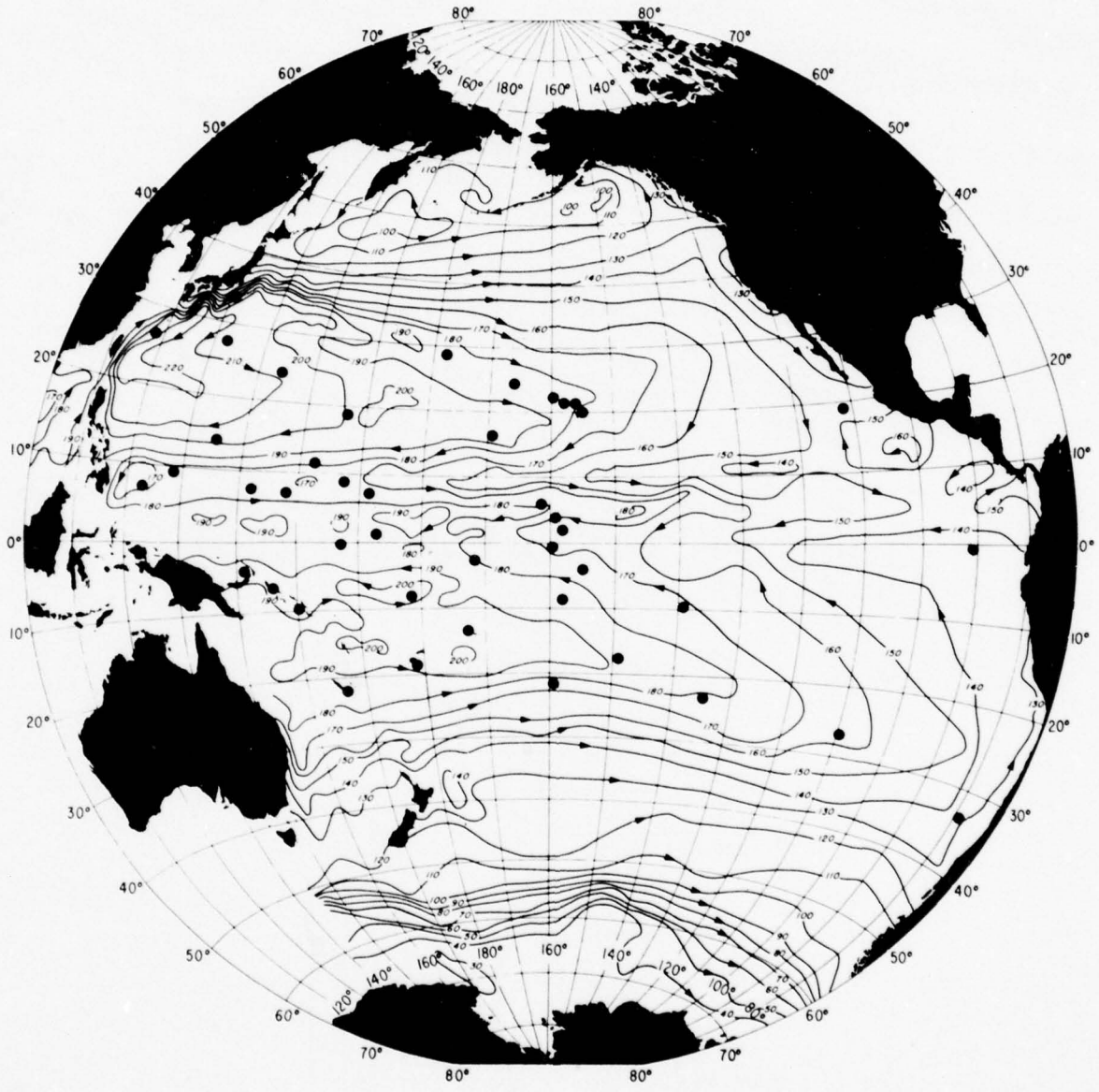

Figure VIII-4. Mean dynamic topography--Pacific Ocean; contours are dynamic centimeters//1000 decibar level. (from Ref. VIII-3)

Table VIII-4. Monthly dynamic height (dyn m)//1000 m, Oahu to San Francisco; NODC historical data.

*Modified Canadian Square	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1117-06	1.83	1.79	1.91	1.84	1.84	1.85	1.86	1.80	1.86	1.90	1.85	1.68
-26	1.87	1.90	1.80	1.78	1.81	1.87	1.88	1.88	1.94	1.90	1.84	1.82
-24	--	1.77	1.93	1.82	1.86	1.83	1.85	1.85	1.86	1.85	1.78	--
-42	--	1.69	1.80	1.75	--	1.80	--	--	1.91	1.93	1.86	--
-40	1.79	1.71	1.97	1.75	1.76	1.76	1.77	1.85	1.81	1.80	1.81	1.82
1116-68	--	1.70	1.72	1.65	1.73	1.70	--	--	1.81	1.77	1.68	1.75
-66	1.81	1.61	1.76	1.68	1.73	1.70	1.84	1.71	1.70	1.79	1.72	--
-84	--	1.62	--	1.64	1.75	1.66	--	--	1.72	1.72	1.63	--
-82	--	1.61	1.60	1.64	1.61	1.64	--	1.70	1.65	1.69	2.22	1.62
1216-00	1.60	1.58	1.60	1.59	1.61	1.63	1.63	1.64	1.66	1.65	1.64	1.63
1215-08	1.64	1.58	1.60	1.59	1.61	1.62	1.64	1.66	1.66	1.65	1.67	1.63
-28	1.63	1.52	1.57	1.55	--	1.58	1.58	--	--	--	1.58	--
-24	1.55	--	1.55	--	1.56	1.58	1.59	--	1.63	--	1.61	1.59
-42	--	--	1.54	--	--	--	--	--	--	--	1.52	1.54
-40	1.49	1.48	1.50	1.46	1.50	1.57	1.61	1.51	1.56	--	1.48	1.51
1214-48	1.49	1.47	1.46	1.47	1.48	1.50	1.49	1.48	1.52	--	1.55	1.45
-66	1.41	1.63	1.42	1.31	1.40	1.38	1.46	1.57	1.43	1.47	1.43	1.38
-64	1.29	1.34	1.31	1.29	1.32	1.38	1.31	1.33	1.40	1.31	1.30	1.31
-62	1.29	1.31	1.31	1.21	1.24	1.23	1.26	1.30	1.38	1.31	1.31	1.43

*See Figure V-3 for location of squares.

Table VIII-5. Dynamic height differences from 1500 m to 1000 m, dyn cm, for Oahu to San Francisco; NODC historical data.

Modified Canadian 2° x 2° Square	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1117-06	--	--	--	--	--	--	--	--	--	25	29	--
-26	--	--	44	--	38	--	--	--	25	--	--	--
-24	--	--	20	24	--	37	--	--	--	--	--	--
-42	--	--	--	45	--	39	--	--	36	--	--	--
-40	36	--	14	32	--	--	--	--	--	32	--	--
1116-68	--	--	--	--	--	--	--	--	--	--	--	--
-66	--	--	--	--	--	--	--	--	--	--	--	--
-84	--	--	--	--	--	--	--	--	--	--	--	--
-82	--	--	--	--	--	--	--	--	--	--	--	--
1216-00	--	--	--	32	36	38	38	35	40	34	--	--
1215-08	--	--	--	--	--	45	--	--	36	37	--	--
-28	--	--	--	--	--	--	--	--	--	--	--	--
-24	--	--	--	--	--	--	--	--	--	--	--	--
-42	--	--	--	--	--	--	--	--	--	--	--	--
-40	--	--	40	--	--	--	25	42	36	--	--	33
1214-48	--	32	--	--	40	--	33	--	38	--	37	--
-66	34	--	30	--	--	--	--	--	--	--	35	--
-64	30	32	29	--	23	46	35	29	19	--	40	33
-62	35	38	29	--	39	--	--	--	39	30	33	--

VIII-3. Precision Satellite Altimetry

The author participated in a workshop on "Quasi-geostrophic and Mesoscale Aspects of Ocean Dynamics" in connection with Ref. VIII-6, during which the required and existing capabilities of satellite altimetry were discussed. The results reported in this section were the consensus of that meeting.

Precision satellite altimetry may allow the measurement of geopotential topography over the oceans. The recent launching of SEASAT-1 demonstrated that a short-pulsed altimeter is capable of resolving ±10 cm in change of surface elevation. This is an order of magnitude better than that aboard GEOS-3.

However, the measurement of absolute surface elevation requires a priori knowledge of the shape of the geoid to within the resolutions required for measuring surface elevation. The best geoid to date is accurate to within ±1.0 m. An accurate local geoid can be determined by removing geoidal variability through data processing. The variability of the ocean surface elevation with respect to such a local geoid can then be determined accurately to within instrumental errors.

The information in Table VIII-6 is a condensed compilation of the various ocean systems that have measurable geopotential heights, and indicates the required satellite altimeter capability.

The working group reviewed the major ocean systems in terms of their geopotential heights, horizontal length and time scales, and current magnitudes. The results of the discussions are summarized in the first four columns of Table VIII-6. The required altimeter capabilities for measuring the physical properties of ocean dynamical systems are shown in the next three columns. Different processes are impacted differently by geoidal errors, tidal elevation changes, orbital errors, and instrumental techniques. These effects, investigated by other working groups of the Symposium, are summarized in the last four columns in the table.

From such considerations and the information summarized in Table VIII-1, three categories of oceanic processes are identified: (a) those that can be studied with existing technology, (b) those that require an improved altimeter resolution (±5 cm expected in 5 years), and (c) those that require an improved best geoid to ±10 cm (expected in 10 years).

(a) Ocean Systems That Can Be Studied with Existing Technology

1. Mesoscale eddies
2. Western boundary currents
3. Antarctic and circumpolar currents
4. Curvature change in major current systems
5. Seamounts and trenches

Table VIII-6. Ocean dynamical systems and required satellite altimeter capability. (from Ref. VIII-6)

	SCALES OF PROCESSES				REQUIRED ALTIMETER CAPABILITY			INVESTIGATED BY THE OTHER WORKING GROUPS			
	RANGE	LENGTH SCALE	TIME SCALE	SPEED/ VELOCITY	VERTICAL RESOLUTION	HORIZONTAL RESOLUTION	FREQUENCY OF COVERAGE	GEOID AND ZERO FREQUENCY	TIDE	ORBIT	MEASUREMENT TECHNIQUES
SEAMOUNTS AND TRENCHES	10 m	100 km	$>10^3$ years	0	1.0 m	10 km		O.K.	O.K.	O.K.	O.K.
EDDIES - STATISTICS - TRACKINGS (Middle Latitude)	50 cm	100 km	2 years (Decay)	2 m/sec Velocity 2 km/day Transport	±10 cm	10 km	1 week	O.K.	Not Required	Not Required	Several Satellites Satellite with Multi-beam Altimeter
GENERAL BASIN WIDE CIRCULATION (Position and Strength Variations)	1 m	5000 km	2-10 years	2 m/sec	±5 cm	50 km	1 mo.	10 cm or better Global Geoid	5 cm	5-10 cm	Intersecting Orbit
WESTERN BOUNDARY - CURRENT - POSITION & STRENGTH VARIATION	1 m 50 cm	100 km Wide 400 km Meander	1 week 20 days	2 m/sec 10 km/day	±10 cm	10 km	1 week	10 cm Local Geoid	None	None	Several Satellites Satellite with Multi-beam Altimeter
EASTERN BOUNDARY CURRENTS	20 cm	300 km	10 days	20 cm/sec	±5 cm	10 km	1 week	10 cm Local Geoid	None	10 cm	Improved Altimeter to ±5 cm
ANTARCTIC AND CIRCUMPOLAR CURRENTS	1.2 m	500 km	20 days	1 m/sec	±10 cm	20 km	1 week	10 cm Local Geoid	None	10 cm	70° Inclination
SEA STATE	10 m	100 km	1/2 day			10 km	Concurrent with Height	None	None	None	None
UPWELLING CURVATURE CHANGE	20 cm 1 m	100 km	1 week	1 m/sec	±5 cm ±10 cm	±10 km	1 week	10 cm Local Geoid	None	10 cm	Improved Altimeter to ±5 cm
EQUATORIAL CURRENT - EDDIES - CURRENT	40 cm 15 cm	200 km 1200 km	20 days 35 days	1 m/sec 40 km/day	±5 cm	20 km 50 km	1 week	10 cm Local Geoid	None	10 cm	Improved Altimeter to ±5 cm

(b) Ocean Systems That Require ±5 cm Altimeter Resolution

1. Eastern boundary currents
2. Upwelling
3. Equatorial currents

(c) Ocean Systems That Require ±5 cm Altimeter Resolution and ±10 cm Best Global Geoid (Possible in 10 Years)

VIII-4. References

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VIII-5. "Mesoscale variations in the deep sound channel and effects on sound propagation," W.J. Emery, T.J. Reid, J.A. DeSanto, R.N. Baer, and J.P. Dugan (to be published).

VIII-6. "International Symposium on Interaction of Marine Geodesy and Ocean Dynamics," October 10-13, 1978, Miami, Florida.

General: Drs. K. Wyrtki (University of Hawaii), N.E. Huang (APL-JHU), and O.H. Shemdin (JPL, Cal. Tech.) contributed to the information on satellite altimetry for oceanographic applications. Dr. F.J. Lerch (NASA) supplied many reprints and much data. Dr. Oscar K. Huh (Louisiana State University) supplied significant information on satellite imagery data.

IX. EXTREMELY LONG RANGE ACOUSTIC PROPAGATION

IX-1. Time-Dependent Acoustic Effects

The present fixed acoustic path under study between Oahu and San Francisco (3835 km, 133 Hz) is the longest fixed path ever attempted. The previous longest fixed path was from Eleuthera to Bermuda (1250 km, 406 Hz). The mean propagation loss was about 120 dB for the 1250 km path. For the longer path, we estimate an additional loss of 32 dB due to cylindrical spreading, while there is expected to be 8 dB less absorption loss for the 133 Hz signal even though the path is three times as long. Thus the expected propagation loss is 144 dB. The travel time over the longer path is expected to be 42.6 minutes. Presently available acoustic models are expected to explain any important deviations from these values.

For the Eleuthera-Bermuda path, the propagation loss and phase record for cw signals were recorded for a period of five months (Ref. IX-1). Long-period phase and amplitude fluctuations were observed to be qualitatively similar to the short path (50 to 75 km) results for the Straits of Florida. Phase fluctuations associated with ocean tides were a marked feature of the data. Shorter period fluctuations of a few minutes to a few hours were also observed.

Temporal fluctuation data are relatable to environmental fluctuation data and are suitable for the testing and validation of environmental-acoustic propagation. Models are best obtained in fixed-source, fixed-receiver studies with cw or periodic sequence signals (Ref. IX-2). Relationships between acoustical and environmental fluctuations have been studied for periods varying from a fraction of a second to a substantial fraction of a year. Generally the larger the time scale of the environmental phenomenon, the larger the amplitude and phase fluctuations that result from it.

Transmission loss varies both spatially and temporally. Knowledge of spatial variations yields the maximum range of detection and hydrophone array design. Knowledge of temporal variations is required to improve signal processor design and to predict system performance. Also, a study of temporal fluctuations yields information about the oceanic and atmospheric environment.

Acoustic amplitude and phase fluctuations have been related to: surface waves, internal waves, diurnal and semidiurnal tidal phenomena, Rossby waves, solar heating, changes in tidal phenomena due to lunar declination, movements of large air masses and associated pressure differences, seasonal effects, currents, and finestructure.

Figure IX-1 (Ref. IX-1) shows the two-day mean and variance of the transmission loss over the 1250 km Eleuthera-Bermuda path extended over a 5-month period. Note the long period 20-dB change as well as the fairly stable 7-dB standard deviation.

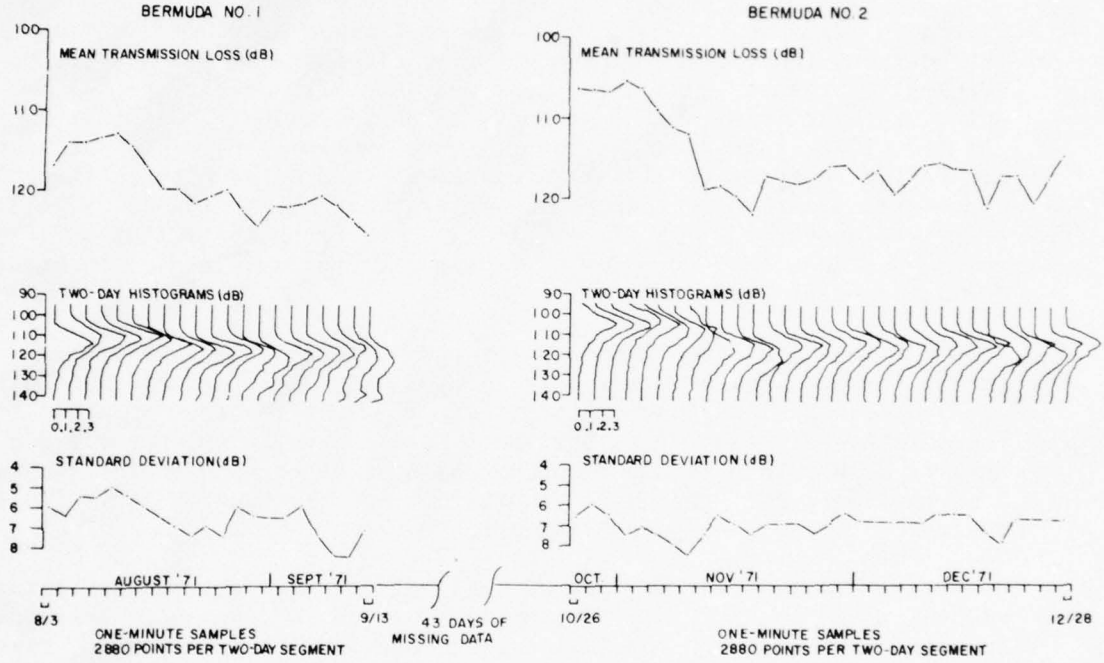

Figure IX-1. A time-dependent statistical characterization of the Bermuda amplitude data over a 5-month period. Each data point for the mean and standard deviation and each histogram cover 2 days (2880 points) of amplitude data.

IX-2. Range-Dependent Effects

There have been numerous studies (Ref. IX-3) of the propagation of sound through single mesoscale features such as a warm ring (eddy), a cold ring (eddy), a front between water masses, the Gulf Stream, and a Rossby wave. Internal wave effects are not expected to be important (Ref. IX-4), but this remains to be seen. The mesoscale features have been modeled deterministically since changes occur in time periods that are long compared with the acoustic propagation time. The inverse problem of describing the oceanographic features from the acoustic behavior is being studied concomitantly (Ref. IX-3).

When sound is propagated over a fixed path through more than one water-mass type and the associated fronts, currents and eddies, there are range-dependent effects because of changing bathymetry, tides, currents, and sound speed profiles. Uniform attenuation losses are relatively small compared with such effects as: convergence and divergence of rays, displacements of the sound channel axis, varying cross-sectional area of the deep sound channel, Doppler shifts and spreading, refraction by water currents, and blockage by bottom features. There are also changes of ray direction from sloping continental and island shelves. Redirection of surface scattered energy into the bottom at high grazing angles is also possible due to swells and long gravity waves. Finally, there are certainly tidal period effects. Proper modeling of long range paths may require statistical treatment as well as deterministic parameters, as is discussed in the next few paragraphs.

Guthrie et al. (Ref. IX-5) were the first to show the importance of range-dependent effects through measurements and environmental modeling. Measurements were made between Antigua and Newfoundland at frequencies of 13.89 and 111.1 Hz from a range of 400 km to a range of 2800 km. Convergence zones were observed at long range, and their positions were found to be frequency dependent. The average rate of increase of transmission loss with increasing range was less than that for cylindrical spreading. Four oceanographic regions were required to model the path properly. XBTs were taken every two hours, or 26 km, to a depth of 760 m. Of the approximately 86 casts, 52 were used to obtain the sound velocity profile as a function of range, or one every 43 km. The lengths of the four regions were: Region 1, 1085 km; Region 2, 1287 km; Region 3, 239 km; and Region 4, 10 km. Bathymetry was also determined along the track. It is believed that for the propagation times involved, the spectra plotted vs interference wavenumber represent spatial fluctuations rather than temporal fluctuations.

In Region 2, 1180 to 2467 km, a near-surface sound channel was present which did not trap 13.89 Hz energy but did trap 111.1 Hz energy from the shallow source (21 m). This energy then traveled to long ranges by various leakage mechanisms into the SOFAR channel. At a range of 2790 km, the SOFAR axis rose to 100 m, producing a marked decrease in transmission loss.

In another experiment from Midway Island (177°W, 28°N) in the North Pacific (Ref. IX-6), shots were detonated at 200 m depth along a 1650 km track northeast of the hydrophone located on the SOFAR axis. XBTs were cast every 6 hours, one-third of which covered 1800 m depth. Archival data were used to extend the 1800 m profiles to the ocean bottom. Five of these profiles spaced along the track at 0, 609, 962, 1169 and 1651 km were chosen for ray calculations, because they represented five distinguishable classes. It was found that multipath arrival structure may be identified from ray calculations using the five sound speed profiles and

bathymetric data. The environmental changes affecting the arrival pattern of shots are of long duration. Signatures from shots more than a week apart combined to produce a highly regular pattern. The principal ray paths are "refracted-refracted" (RR).

In Ref. IX-7, Emery et al. have modeled acoustically one of the Northwest Pacific swaths of Wilson and Dugan (Ref. VII-3). A range-dependent parabolic wave equation model was used to calculate expected acoustic behavior along this path. At 50 Hz, the authors find that the resultant sound speed profiles are dominated by mesoscale features which are apparent as large vertical excursions of the sound channel axis depth. A numerical experiment was used to model the low frequency sound propagation along a 250 km path. The acoustic intensity is plotted vs depth and range for a hundred realizations; that is, the source is placed at 100 random points at 300 m depth. It is found that the standard deviation of the ensemble intensity field levels off to a saturation value of 5.5 dB outside the main beam in several tens of kilometers. This variability is estimated to have length scales on the order of 10 km in range and several hundred meters in depth.

The Naval Oceanographic Office surveyed the same general region a year or two later (July and August 1977; Ref. IX-8). They used cw signals (89 Hz and 107 Hz at 95 m depth) and SUS charges (90 m and 18 m depths) to study the acoustic path which was about 1722 km long. This path extended through the middle of the swath region in a NW to SE direction. The environmental objectives of this survey were: (1) to determine the thermohaline and sound velocity structures of the Subarctic-Subtropical Transition Zone, and (2) to characterize the fronts marking this region.

Depth profiles of temperature, salinity and sound velocity were obtained at 26 sites along the path, spaced a distance of 66 km apart. XBT's were dropped hourly when strong horizontal gradients were found. Airborne thermal surveys were also conducted to observe spatial and temporal variations within the Transition Zone. Bathymetry along the track was obtained directly.

Figure IX-2 shows the existence of a warm core eddy about 300 km in diameter occupying much of this part of the Transition Zone which has an average width of 500-1000 km across the Pacific. Figure IX-3 shows the associated sound speed structure.

For comparison with measurements, results are available from range-dependent model computations of the acoustic field. Twelve profiles were used to represent the sound speed environment for this 1600 km (870 n. mi.) path. Seven profiles, 26 km apart, were used to cover the subarctic front which was about 185 km wide. Two profiles covered the subtropical frontal boundary, while one or two profiles covered the more homogeneous regions.

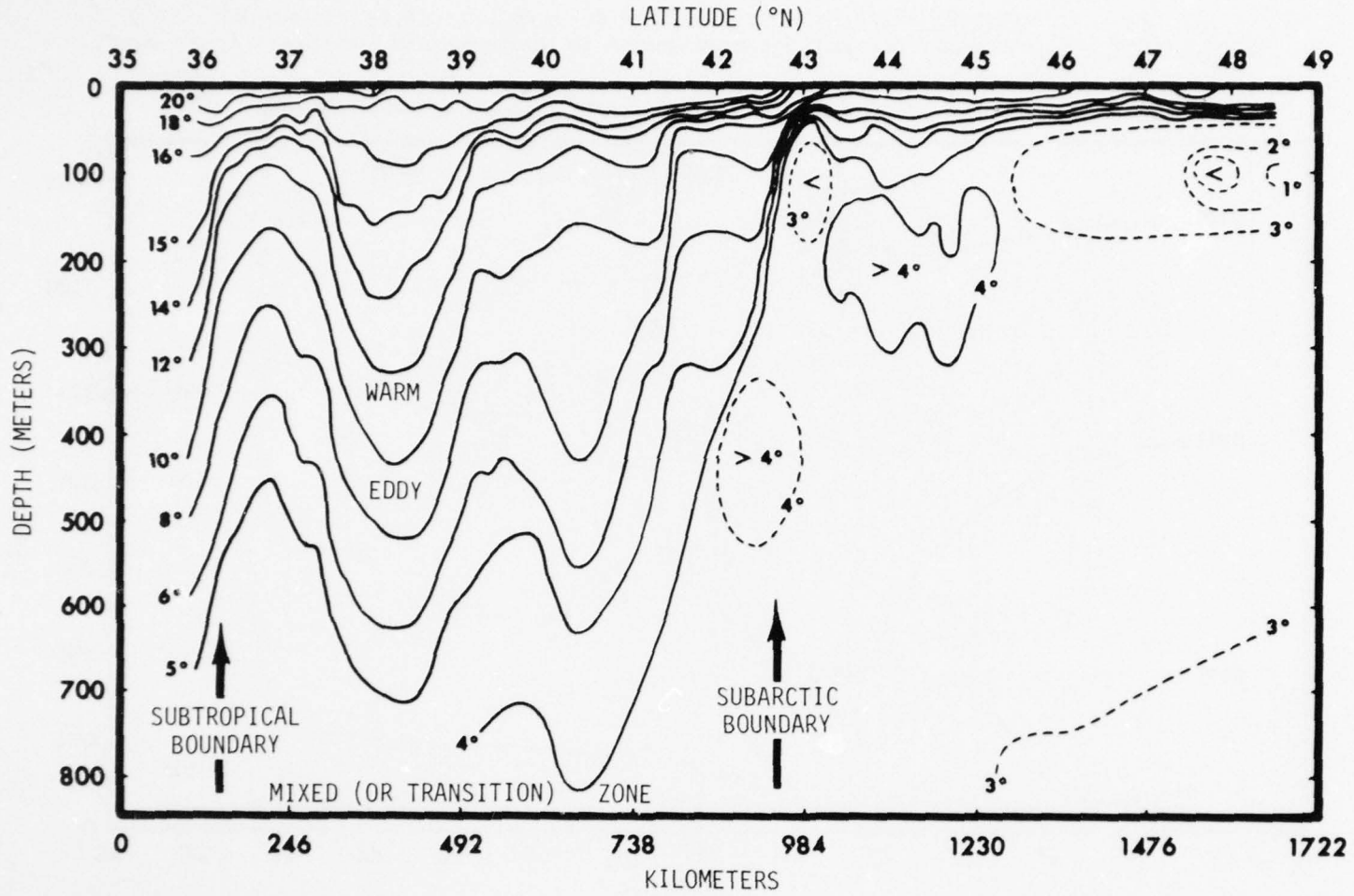

Figure IX-2. Vertical distribution of temperature (°C) between 35°50'N, 170°04'E and 48°30'N, 161°53'E--22-27 July 1977; 1 n. mi. = 1.85325 km. (from Refs. IX-8, 11)

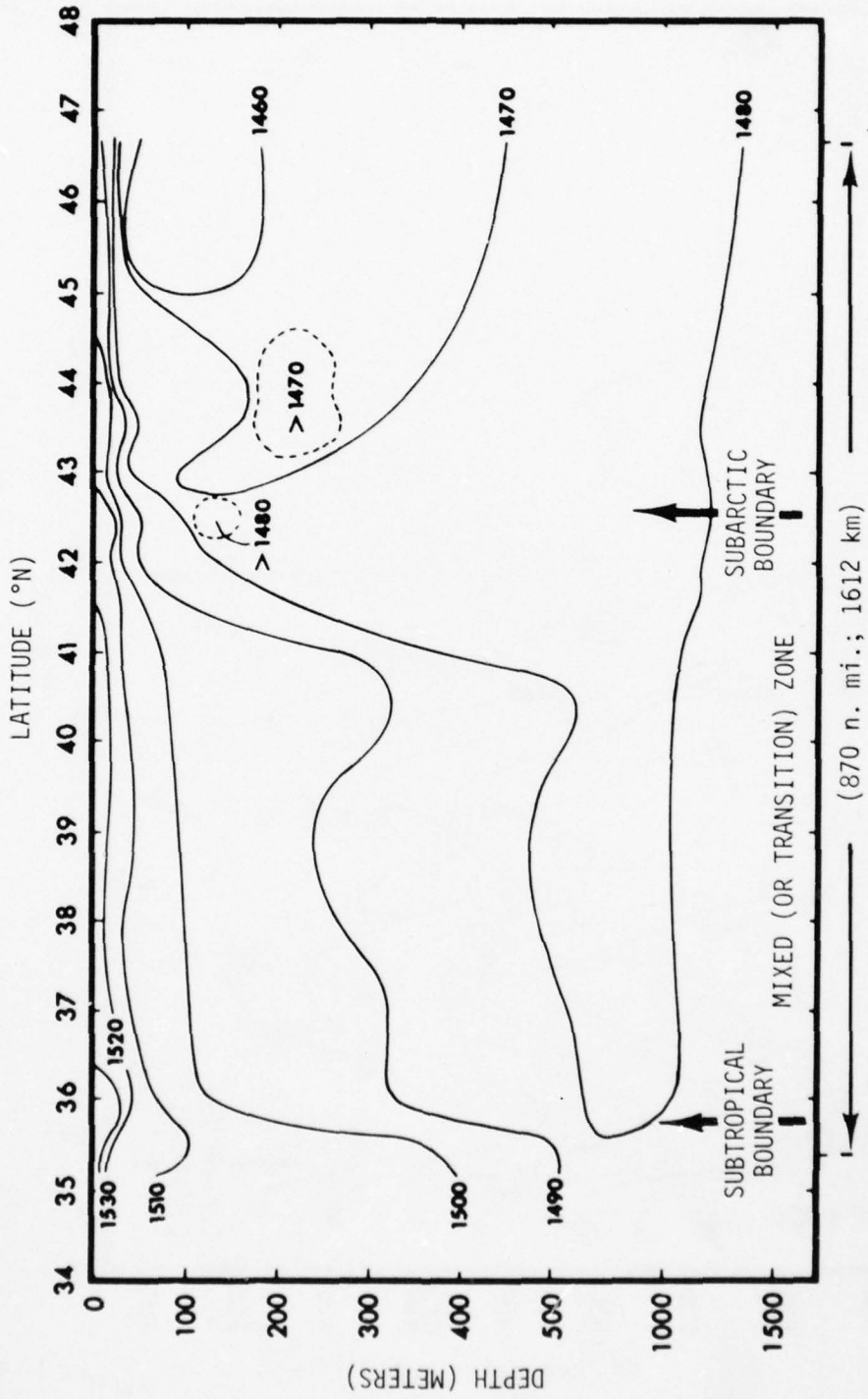

Figure IX-3. Vertical distribution of sound velocity (m/sec) between 35°09'N, 170°44'E and 46°40'N, 159°01'E--28 July - 3 August 1977. (from Refs. IX-8, 11)

In general, when a front is traversed from a warm to cold water mass, the deep sound channel migrates upward along with a narrowing of the channel cross section which concentrates the acoustic energy. A front may introduce additional axially propagating paths from the refracted-surface reflected paths of convergence zones.

The Parabolic Wave Equation (PE) model (Ref. IX-9) and the Multiple Profile Program (MPP) (Ref. IX-10) have been used to study the expected effects of the fronts and eddy of this experiment. Consideration of the range dependence of the environment introduces a gain of about 10 dB over the constant environment for the 89 Hz source at 95 m depth. (See Fig. IX-4a.) Although not shown in this figure, the source depth of 95 m reduces the propagation loss over that at 18 m by about 5 dB in the frontal region. An increase in frequency from 89 Hz to 107 Hz increases the loss by 3 dB.

Figure IX-4b is a plot of the measured propagation loss data. It may be seen that at 375 n. mi. the front produces a gain of about 5 dB instead of the calculated 10 dB. Note that the transmission loss scales for Figures IX-4a and b are different.

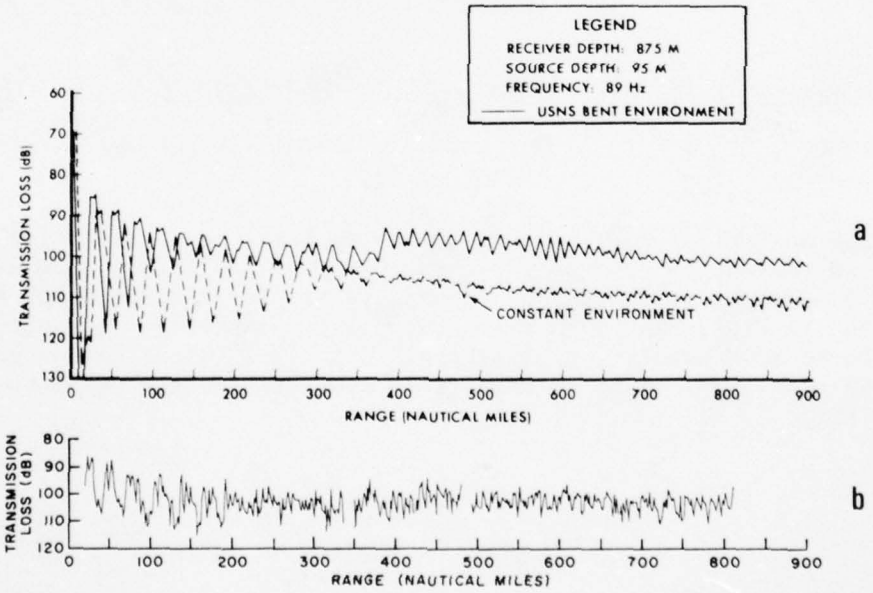

Figure IX-4. a--calculated transmission loss versus range--environmental effects. Range dependent environment versus constant environment. (from Ref. IX-8) b--measured transmission loss versus range. Range dependent environment for conditions specified in legend above. (supplied by Mr. R. Merrifield of NAVOCEANO)

IX-3. Attenuation Coefficients at Very Low Frequencies

There is inconsistency in the attenuation data at frequencies below 100 Hz (Ref. IX-12). Some of the measured attenuation coefficients exhibit a regional dependence. One hypothesis for very low frequency attenuation is the frequency-independent ray diffusion loss model due to volume scattering (Refs. IX-13, 14). Leakage into the bottom out of the deep sound channel is another hypothesis (Ref. IX-15). This would require a minimum at about 50 Hz or less. The existence of a minimum attenuation coefficient at 50 Hz has also been attributed to modal leakage due to near-surface scattering effects (Ref. IX-16). There is a strong suggestion that the scattering agent is depth dependent and dominant in the upper few hundred meters of the ocean. This scattering agent appears to be related to turbulence, water velocity shears, finestructure, and microstructure.

Table IX-1 summarizes the magnitude of these regional attenuation coefficients (adapted from Ref. IX-12).

Table IX-1. Regional attenuation coefficients, dB/km; $f \lesssim 100$ Hz.

Arctic Convergence	Polar	Subpolar	Temperate	Tropical
15.0×10^{-3}	5.0×10^{-3}	2.0×10^{-3}	$2.5 \times 10^{-3} - 0.4 \times 10^{-3}$	0.4×10^{-3}

The absorption coefficient due to the boric acid relaxation at 1 kHz is regionally dependent because of pH variability. (See Ref. IX-17.) A typical pH and sound speed profile for the Northeast Pacific is shown in Figure IX-5. A relatively simple expression for estimating this boric acid absorption is given in Ref. IX-18 along with a geographic plot (Fig. IX-6) of associated contours for the parameter A (f in kHz).

$$\alpha_{B.A.} = \frac{A\ f^2}{1+f^2} + \frac{43.7\ f^2}{4100+f^2}\ \text{dB/km}\ .$$

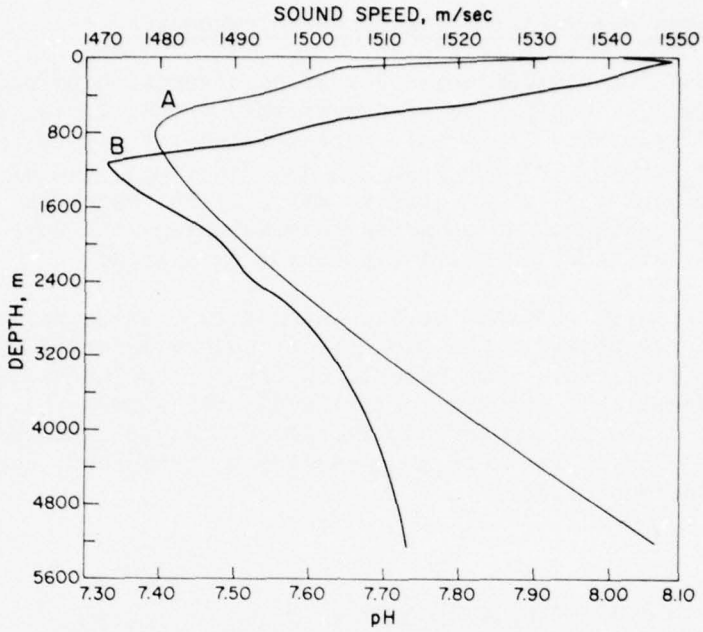

Figure IX-5. Pacific Ocean (Modified Canadian Square 1217; 30° to 40°N, 150° to 160°W). A = sound speed versus depth; B = pH versus depth.

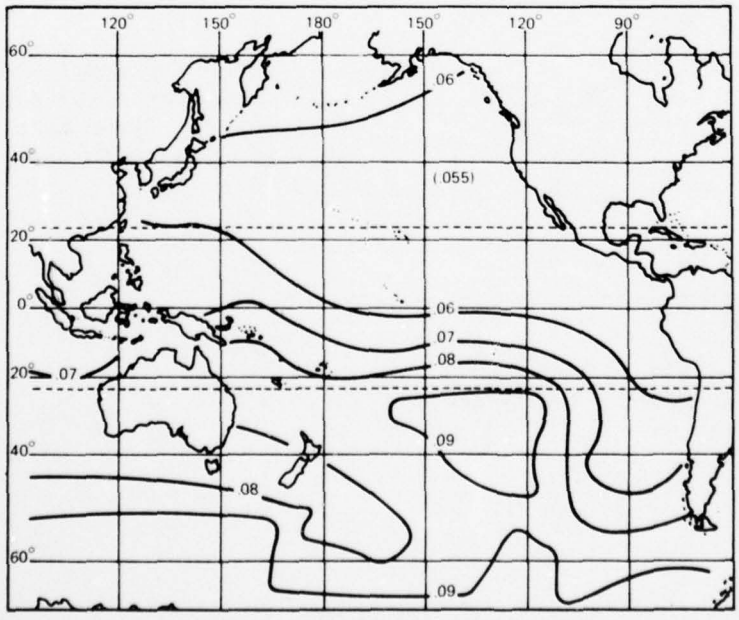

Figure IX-6. Contour plot of the value A in the Pacific Ocean for use with sound absorption equation. A is determined from the pH at the SOFAR axis. (from Ref. IX-18; reproduced with permission)

IX-4. Ambient Noise Field at Very Low Frequencies

Some data on ambient noise levels as a function of depth for the Northeast Pacific Ocean have been published (Refs. IX-19, 20) from the NORDA-LRAPP program. These data were obtained at a site (Site A, 30°N, 145°W) midway between Oahu and San Francisco, and also at a site (Site C, 40°N, 145°W) about 1000 km directly to the north. Considering that the low-frequency noise arose from shipping, the data were used to estimate the attenuation coefficients for this area.

The data were obtained during two separate 24-hr periods and were analyzed in 1/3-octave bands over the frequency interval 10-300 Hz. Median spectral levels were calculated for 10 sec intervals. Figure IX-7 shows the sound axis spectral noise levels for a 24-hr period (period 2) at both sites and at two depths, the sound channel axis and the critical depth. The results indicate a dependence on frequency, hydrophone depth, and sound speed profile.

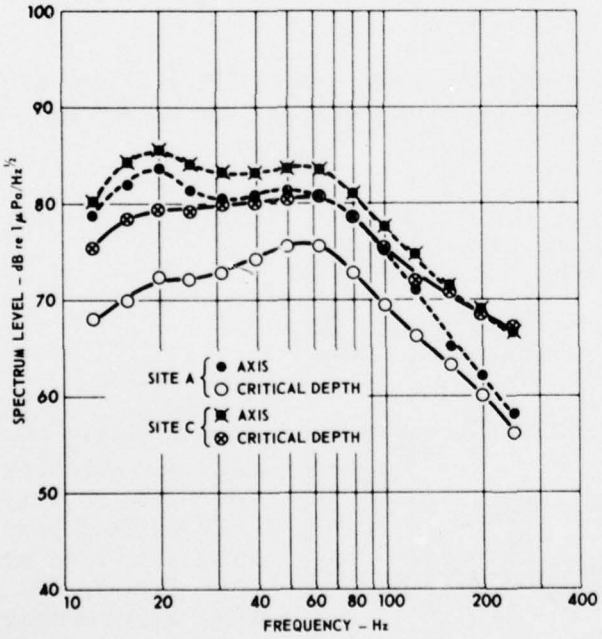

Figure IX-7. Median spectra for axial and critical depths at sites A and C for period 2. (from Ref. IX-19; reproduced with permission)

Figure IX-8 shows the bathymetry and sound speed structure along the 145°W meridian vs latitude. It can be seen that the sound channel axis, the critical depth, and the bathymetry all shoal toward the Alaskan shelf. This figure, in conjunction with Figure V-1, gives more perspective to the problem of predicting acoustic properties for extremely long range paths in the Northeast Pacific.

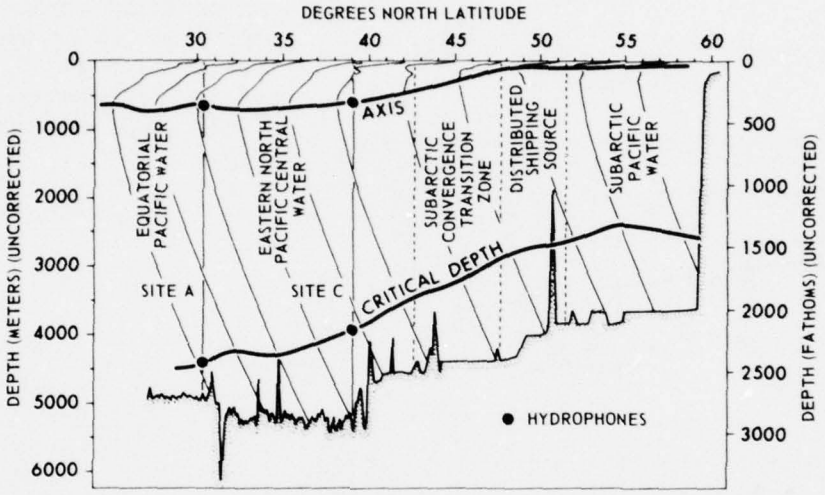

Figure IX-8. Bathymetric and sound-velocity structure; 145°W longitude. (from Ref. IX-19; reproduced with permission)

Figure IX-9 shows that the values of the median spectral noise levels at the sound channel axis are consistently higher at the northern site. The higher northerly noise levels are attributed to the density of distant shipping. The important point is made that there is a decided difference between the axial noise levels and those at critical depth. These data are shown in Figure IX-9 for both sites, and may be used in two ways pertinent to our present objective:

(a) The differences in the two sets of differences (L_N axial - L_N critical) are used to estimate the attenuation coefficient as a function of frequency for the area. These are summarized in Figure IX-10. The symbol α_{OS} stands for the scattering or diffusion attenuation coefficient; α_A is the absorption coefficient; α_W is the sum of the two. The 3 dB difference at 130 Hz for 1000 km leads to an estimated attenuation loss of 11 dB over a 3800 km path.

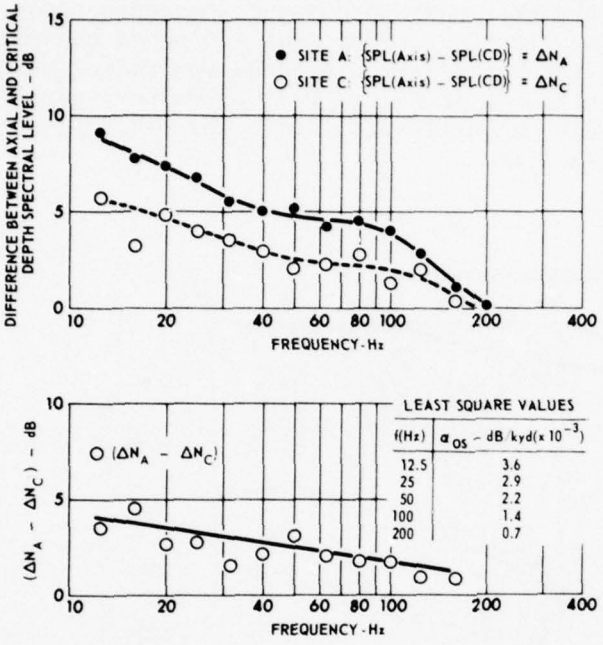

Figure IX-9.
The difference between the axial noise excess (over the critical depth value) at the two sites A and C, as a function of frequency. (from Ref. IX-19; reproduced with permission)

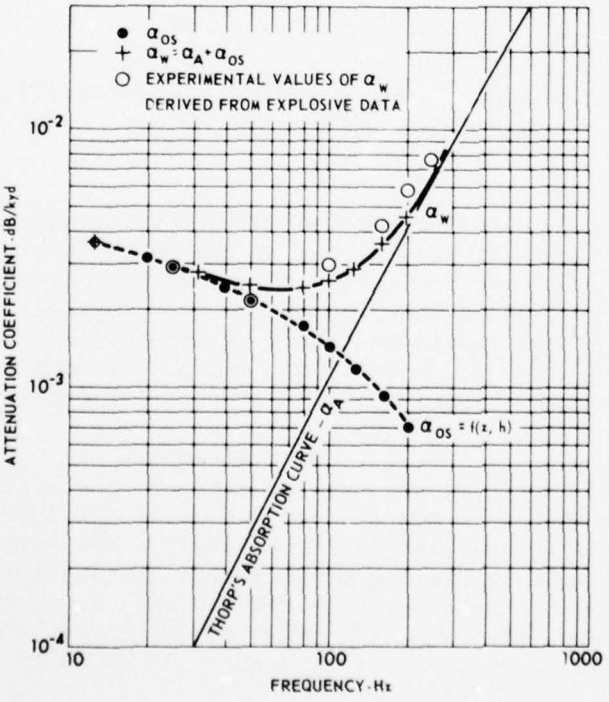

Figure IX-10.
Low-frequency attenuation coefficients for the North Pacific Central Water between sites A and C. (from Ref. IX-19; reproduced with permission)

(b) If the 3 dB difference in noise levels between the sound axis and critical depth at 90 Hz for Site A were to hold everywhere along the path for a signal projected from Oahu, then the shallow array at the sound channel axis off San Francisco would be at least that much better than a deep offshore array below the critical depth.

IX-5. References

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IX-3. See, for example,

(a) "Mesoscale variations in the deep sound channel and effects on sound propagation," W.J. Emery, T.J. Reid, J.A. DeSanto, R.N. Baer, and J.P. Dugan (to be published).

(b) "General analysis of ocean eddy effects for sound transmission applications," R.F. Henrick, W.L. Siegmann, and M.J. Jacobson, J. Acoust. Soc. Am. 62, 860-870 (1977).

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IX-8. "Modeling the impact of oceanographic variability on acoustic propagation in the Western North Pacific," A. D'Amico and L.S. Blumen, NAVOCEANO TN #3440-9-78, August 1978, Bay St. Louis, Mississippi. [Copy supplied by Ms. D'Amico and Ms. Blumen with detailed discussion]

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General: Mr. K.W. Lackie (NORDA) provided the author with a list of unpublished LRAPP reports.

X. CONCLUSIONS

1. It is feasible to use the National Marine Fisheries Service (NMFS, NOAA) ship-of-opportunity XBT data merged with the NAVOCEANO taped historical oceanographic data file to obtain sound speed profiles for use in propagation calculations related to the Northeast Pacific fixed-source fixed-receiver propagation study.

2. The shallow monthly XBT runs must be augmented with 760 m and 1830 m runs.

3. In regions of large horizontal gradients of temperature and/or salinity, XBT drops should be made every 30 km instead of every 120 km.

4. The space-time scale of mesoscale processes must be determined in the regions where propagation measurements are being performed.

5. The position and scale of surface mesoscale features may be estimated by using NMFS' surface temperature deviation contours with respect to 20-year means.

6. Additional synoptic XBT coverage for other locations in the Northeast Pacific may be obtained from the Fleet Numerical Weather Central's data network.

7. Long time-series of temperature at various depths down to 1500 m would be useful in relating environmental variability to acoustic variability.

8. Existing bathymetric (SYNBAPS) and tidal (M_2) (Dahlgren) data banks and retrieval systems appear to be feasible for acoustic modeling.

9. Dynamic height measurements obtained from satellites with ±10 cm altimetry capability may be used to define mesoscale surface features.

10. The suitability of existing acoustic models for propagation loss and time-of-arrival computations must be tested.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Environmental Aspects of a North Pacific Acoustic Fixed-Source, Fixed-Receiver Installation

5. TYPE OF REPORT & PERIOD COVERED
Technical Report
3/1/77 - 3/1/79

6. PERFORMING ORG. REPORT NUMBER
APL-UW-7905

7. AUTHOR(s)
Morris/Schulkin

8. CONTRACT OR GRANT NUMBER(s)
N00014-77-C-0309
MOD P00002

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Applied Physics Laboratory
University of Washington
Seattle, WA 98105

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
62711N

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research, Code 222
Department of the Navy
Arlington, VA 22217

12. REPORT DATE
1 March 1979

13. NUMBER OF PAGES
89

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Technical rept. 1 Mar 77 - 1 Mar 79

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
---

16. DISTRIBUTION STATEMENT (of this Report)

Distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

North Pacific Ocean; Northeast Pacific Tides; Bottom Topography; Sound Speed Provinces; Temperature Field; Mesoscale Variability; Satellite Oceanography; Extremely Long Range Acoustic Propagation; Environmental Acoustics; Underwater Acoustics; Sound Transmission in the Ocean; Ocean Weather.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Office of Naval Research (Code 222) is sponsoring an experimental program in the Northeast Pacific Ocean to investigate long-term variations in propagation loss and travel time between a fixed source and fixed receiver over extremely long paths. This report considers environmental factors which are expected to be important for acoustic modeling and prediction, particular attention being given to mesoscale features, or "ocean weather." Existing and planned environmental data sources and (cont.)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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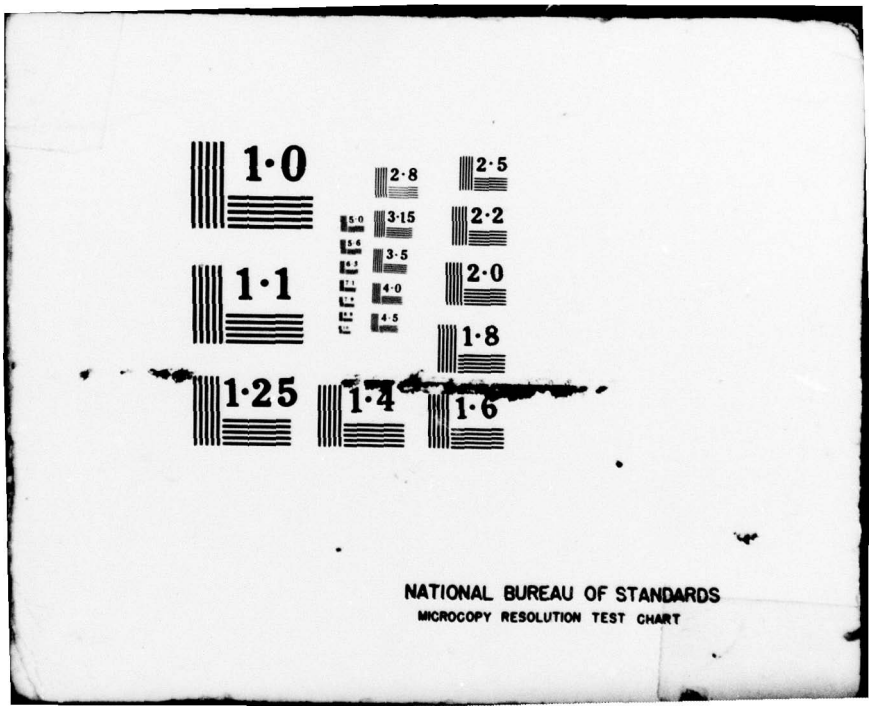
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20. ABSTRACT (continued)

formats are reviewed in terms of the requirements. Cost-effectiveness is emphasized. Monthly weeklong shallow XBT (480 m) sampling of the 3835-km Oahu to San Francisco path by the National Marine Fisheries Service (NOAA) ship-of-opportunity program is found to serve well as a basis. However, the sampling depth must be increased beyond the sound channel axis at about 800 m, and the spacing of drops should be reduced to about 30 km in the vicinity of sharp temperature and salinity gradients. A program has been implemented to merge the taped historical oceanographic station data file (NAVOCEANO) with synoptic XBT and salinity data (NMFS). Available bathymetric (NORDA) and M_2 tidal (NSWC) data banks appear to be quite satisfactory. It is highly desirable to obtain long-term time-series temperature variability data down to depths below the sound channel axis using thermistor arrays at a suitable location along the path. The use of satellites and remote sensing aircraft to supplement the existing data acquisition programs is strongly recommended. Existing computer models of extremely long-range acoustic transmission loss verify relatively large measured range-dependent effects upon crossing fronts, currents, and eddies. The results of previous long-term time-series measurements of propagation loss for the 1250-km Eleuthera-Bermuda fixed path at 406 Hz are presented as a reference.

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