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28 June 2016

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Subj: ONR Grant# N00014-13-1-0053, "Deep Water Acoustics"

Encl: (1) Final Technical Report for Subject Grant
(2) Publications and Presentations
(2) SF298 for Enclosure

Enclosure (1) is the Final Technical Report for the subject grant. Enclosure (2) recaps publications and presentations associated with this grant, and Enclosure (3) is the SF 298 form. These documents constitute the Final Technical Report and deliverable for ONR Grant# N00014-13-1-0053.

cc: Grant & Contract Administrator, APL-UW
Office of Sponsor Programs, UW
ONR Seattle – Evan Wood and Kyoohui Beal
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Deep Water Acoustics

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Office of Naval Research

Award Number N00014-13-1-0053

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) and Deep Water Acoustics programs at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of this research is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the Deep Water Acoustics research are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employed a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities were funneled through two primary avenues. ***The North Pacific Ambient Noise Laboratory***, operated and maintained by APL-UW, provided a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consisted of legacy SOSUS hydrophone receivers in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory.

The second avenue included highly focused, comparatively short-term experiments.
We have completed a pilot study/engineering test and an experiment in the ***Philippine Sea*** called **PhilSea9** and **PhilSea10**, respectively [1]. See Figure 1. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the Distributed Vertical Line Array (DVLA) from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT).

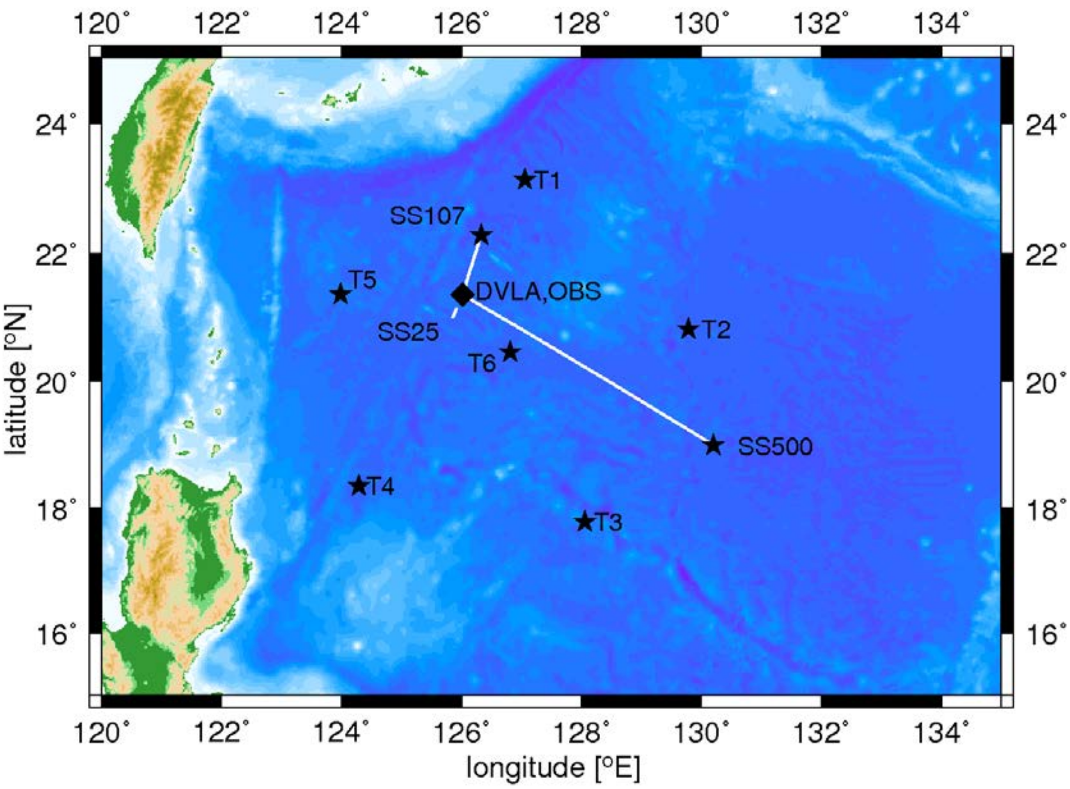

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

Modeling and data analysis efforts that were made under this ONR Postdoctoral Fellowship related to the measured fluctuations in low-frequency acoustic signals received over nominal 107- and 510-km ranges during the PhilSea09 Pilot Study/Engineering Test and the PhilSea10 Experiment [1]. The efforts relating to PhilSea09 will be described first, followed by those relating to PhilSea10.

Acoustic paths for the 107-km range in PhilSea09 had one, two, or three upper turning-points (UTPs). Observed in the intensity records for some of the paths with a single shallow UTP were fades of up to 10 dB, with durations similar to those of the strong local internal tides. The paths with two or three UTPs did not exhibit these long-duration fades.

Predictions of the scintillation index, (SI, a normalized variance of intensity) were made with a Monte Carlo Parabolic Equation (MCPE) computer model [2, 3] to test this model's ability against the PhilSea09 measurements. The MCPE model included perturbations to a background sound speed due only to random, horizontally-isotropic internal wave vertical displacements [4, 5]. The predictions were in agreement with the measurements for acoustic paths that did not exhibit the deep fades. The SI of the measurements greatly exceeded the MCPE model predictions for those paths which did have deep fades. The influence of an oceanographic process other than the random internal wave displacements is suspected to have caused the deep fading–in particular, the strong local internal tides at the site of the experiment.

The modeling and data analysis efforts relating to PhilSea09 consisted of three parts: construction of a plane-wave internal-tide simulator and analysis of environmental data to determine parameters in that simulator, parabolic equation propagation calculations, and Hamiltonian ray-trace calculations.

A computer model that simulates vertical fluid displacements by the internal tide was constructed and adjusted to reflect the internal tide strength at the site of the PhilSea09 Pilot Study/Engineering Test. Vertical mode functions were calculated using buoyancy-frequency profiles measured at the PhilSea09 site.The output of the simulator was a range-depth ’slice’ of sound speed that consisted of a range-independent background profile that was perturbed by vertical fluid displacement at a given time in the evolution of the internal tide; thus, range-depth slices were output at one-hour time steps. These perturbed sound-speed slices were used as the environmental input for parabolic equation calculations.

Broadband acoustic propagation was computed at a center frequency of 284 Hz using the Navy Standard Parabolic Equation split-step Pade algorithm [6] (NSPE, hereafter referred to as PE). The intensity of the arrival which had the path with a single shallow UTP was shown to vary as the internal tide was evolved in time. This result was interesting, and provided some evidence that the internal tide was a plausible mechanism for the long-duration fading–but the actual physical mechanism by which the changes occurred could not be determined readily from the parabolic equation output. The employment of another method for calculating the propagation therefore became necessary.

The Hamiltonian ray-tracing model used in this work was written by Dr. Frank Henyey of APL-UW, and converted to the Matlab language by Dr. Dajun Tang, also of APL-UW. One advantage offered by the Hamiltonian approach is that perturbation relations (also known as Jacobi equations) can be derived, which give information about features of the environment that are most important in controlling the propagation. Another advantage of using a ray-trace model is that the positions of caustics along the path can be output– which was the key to understanding the parabolic equation result. Rays were traced through the same range-depth sound-speed slices as used in the PE.

NEW RESULTS

The results from the work described above are included in a paper [7] that presents a mechanism by which the observed acoustic intensity is made to vary due to changes in the acoustic path that are caused by internal-tide vertical fluid displacements. The position in range and depth of large-scale caustic structure is determined by the background sound-speed profile. Internal tides cause a deformation of the background profile, which changes the positions of the caustic structures–

introducing slow intensity changes at a fixed position in depth and range. The parabolic equation and Hamiltonian ray-tracing calculations described above indicate that internal tides could cause enhanced variability in the intensity in the form of slow changes. Furthermore, the calculations demonstrate how large scale perturbations to the index of refraction can result in intensity fluctuations–contrary to conclusions of previous theoretical work.

The efforts relating to PhilSea10 consisted of analysis of environmental data that were collected at the experiment site and MCPE simulations done for comparison to the measured acoustic fluctuations. CTD data collected by instruments located on the receiving array mooring and in CTD casts were analyzed to determine appropriate environmental parameters for the MCPE simulations. Dr.White conducted broadband (MCPE) simulations at center-frequencies of 75, 200, and 300 Hz, which were reduced and analyzed for comparison to at-sea measurements and theoretical predictions. He also analyzed CTD data taken at the site to determine appropriate environmental parameters for the MCPE simulations. A comparison between MCPE and measured data at 200 and 300 Hz for pulse spread was made in [8].

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the Deep Water project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others.

PUBLICATIONS

Andrew W. White, Frank S. Henyey, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi. Acoustic intensity fluctuations and internal tides: An unexpected connection. *J. Acoust. Soc. Am.*, submitted.

R. K. Andrew, Andrew Ganse, A. W. White, J. A. Mercer, P. F. Worcester, M. A. Dzieciuch, and J. A. Colosi. Low-frequency pulse propagation over 510 km in the Philippine Sea: A comparison of observed and theoretical pulse spreading. *J. Acoust. Soc. Am.*, in press.

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[7] Andrew W. White, Frank S. Henyey, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi. Acoustic intensity fluctuations and internal tides: An unexpected connection. *J. Acoust. Soc. Am.*, submitted.

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North Pacific Acoustic Laboratory and Deep Water Acoustics

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Award Number N00014-13-1-0053
Award Number N00014-14-1-0218

LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) and Deep Water Acoustics programs at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of this research is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

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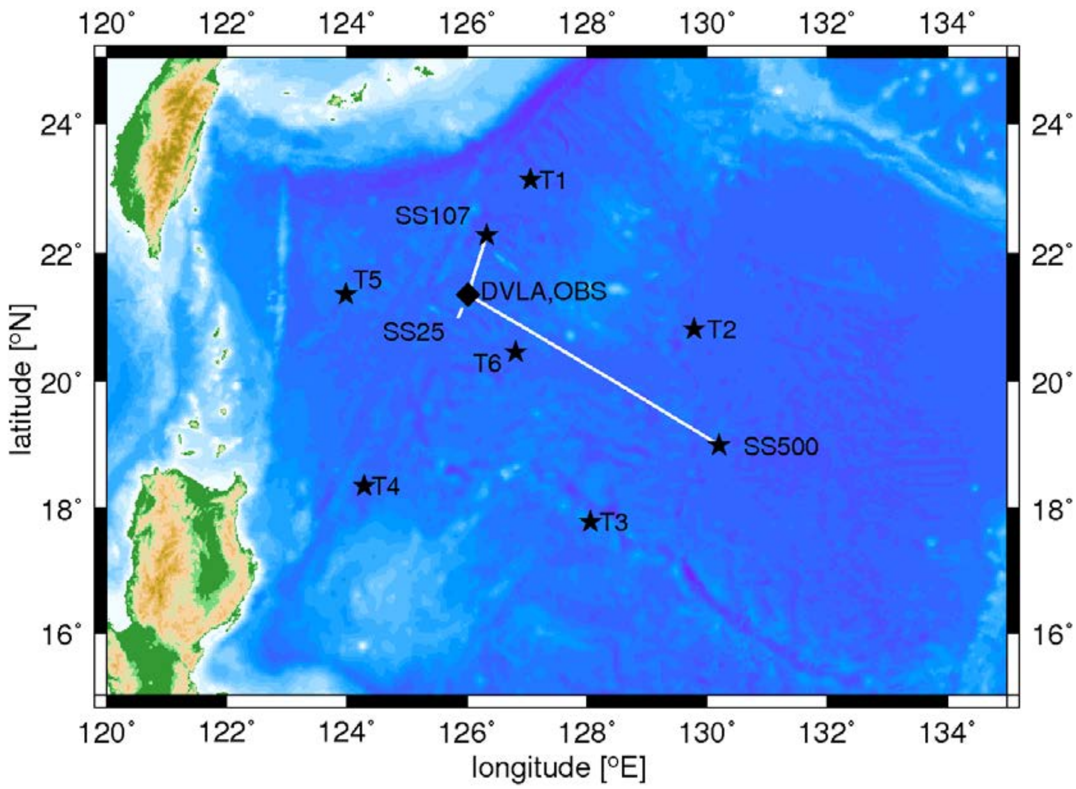

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

I. Award Number N00014-13-1-0053

This post-doctoral award included analysis of a subset of the CTD measurements made at the DVLA during PhilSea10; design, construction, and completion of the broadband, 500-km-range MCPE simulations for center frequencies of 200, 300, and 81 Hz; some comparisons of the simulated data to measured data from PhilSea10; and modeling with broadband PE and Hamiltonian ray-trace codes, of propagation through internal-tide (IT) perturbed environments--relating to PhilSea09. Dr. White has prepared, and sent to co-authors, a manuscript that describes the IT results [2]. The IT work and conclusions are described in New Results Section I below.

II. Award Number N00014-14-1-0218

During this award period Dr. Mercer retired from his full-time position at the University of Washington and was re-appointed to a part-time position. In this new position, the Director of the Applied Physics Laboratory has assigned the following responsibilities: Dr. Mercer "will collaborate with APL scientists and engineers using expertise in deep water acoustics in the effort of processing and analyzing the acoustic transmissions from the PhilSea10 Experiment. As the PI, (Dr. Mercer) will continue to play a role in the complete research process, including managing the project and technical reporting. These duties are completed through frequent collaborations with other members of the Acoustics Department. Additionally, (Dr. Mercer) will be providing advisement to graduate students as well as the national funding agencies and will also continue to supervise a post-doctoral research associate on the project as well."

Results of this effort are shown in a New Results Section II below.

NEW RESULTS

I. New Results Award Number N00014-13-1-0053

During PhiSea09 the acoustic intensity of one of the ray paths exhibited fades of up to 10 dB that lasted 18 and 12 h, respectively [3,4]. The modeling that is presented in this section was done to test the hypothesis that the internal tide (IT) caused these intensity fades. Theoretical considerations would lead one to believe that sound-speed inhomogeneity on scales as large as those of the tides should not affect the intensity (e.g. Desaubies (1978) [5]) - however, a viable alternative hypothesis is not obvious. The results of this work indicate that the IT could cause intensity fluctuations.

The IT environmental models consisted of plane waves traveling due East; the model included only the first vertical eigenmode associated with the frequency of the diurnal tide. The amplitude of this eigenmode was adjusted according to the variance of the vertical displacement measured on microCAT CTDs mounted on the DVLA during PhilSea09.

Displacement $\zeta(z, r, T)$ in the internal-tide model was given by

$$\zeta(z, r, T) = a\, \psi_1(z) \exp(i\, [\omega_1 T + \mathbf{k}_h \cdot \mathbf{r}])$$

in which $\psi_1(z)$ is the first mode of vertical displacement, a is the modal amplitude, ω_1 is the modal phase speed, $\mathbf{k}_h$ is the horizontal wavenumber vector, and $\mathbf{r}$ is the vector pointing from SS107 to the DVLA. The angle α that is listed in table 1 is the angle between the vectors $\mathbf{k}_h$ and $\mathbf{r}$. The evolution time of the internal tide was T, where

$$T \in \{1, 2, 3...24\} \text{ (hour).}$$

Satellite measurements analyzed by Zhao (2014) [6] (see his figures 4 and 5) suggest that the Luzon Strait, which lies roughly 500 km due west of the site of the experiment, is the major source of the diurnal tide at the site of PhilSea09. That analysis took a time-average over multiple years, while PhilSea09 was conducted over a span of only approximately 2.5 diurnal periods; presumably, the relative contributions to the internal tide from various local bathymetric features varies with time (and, therefore, so does the tide’s direction). We modeled the extreme cases of acoustic propagation anti-parallel (α = 180°) and perpendicular (α = 90°) to $\mathbf{k}_h$ to understand the effect of this uncertainty.

The presence of mesoscale variability at the location of the PhilSea09 pilot study was seen in SSH measurements and corroborated with the CTD timeseries recorded by the CTD instruments on the DVLA [3,4]. Single profiles from CTD casts made during PhilSea09 were low-pass filtered to include only scales larger than 100 m, and were then used as representative range-independent background profiles to be perturbed by the internal tides. Comparison of results between the different profiles provided information about the uncertainties caused by a limited knowledge of the background sound speed.

A summary of the model environments used for both the Hamiltonian ray-tracing and the PE calculations is given in Table 1.

Table 1: Simulated environments. $\alpha_0 \approx 107°$, and is an estimate of the angle α during PhilSea09, made from ADCP measurements at the site of the DVLA.

Sim.	A	B1	B2	B3	C	D	E	F
Prof. #	0	4	4	4	5	10	16	20
α	α_0	90°	180°	α_0	α_0	α_0	α_0	α_0

Broadband propagation through perturbed range-depth ocean slices was calculated using the Navy Standard Parabolic Equation (NSPE) code. The arrival corresponding to path ID-3 was windowed out from the resulting timefronts and Fourier-transformed. The absolute square of the Fourier bin containing the 284-Hz contribution was taken to be the intensity—as was done in the case of the data from PhilSea09. The intensity vs. depth for profile c_4 at times T $\in\{1, 2, 3...24\}$ over the depth-span 800m to 1500 m is shown in Figure 2 below.

As can be seen in Figure 2, there is a depth-dependence of intensity over the span of depths shown, that is then translated in the vertical as the internal tide evolves in time. At a given receiver depth, this translation results in a changing intensity with time.

Some questions about the prediction noted in the previous paragraph occur to the authors: Is the direction of the internal tide relative to the direction of acoustic propagation (and thus the range-dependence of vertical displacement) important? Why is the acoustic intensity depth-dependent? Why does the variation of intensity with depth translate vertically with the internal tide?

The first question was answered by comparison of simulations B1 and B2: the angle between acoustic propagation and the internal tide doesn't significantly affect the magnitude of the intensity change at a given receiver depth.

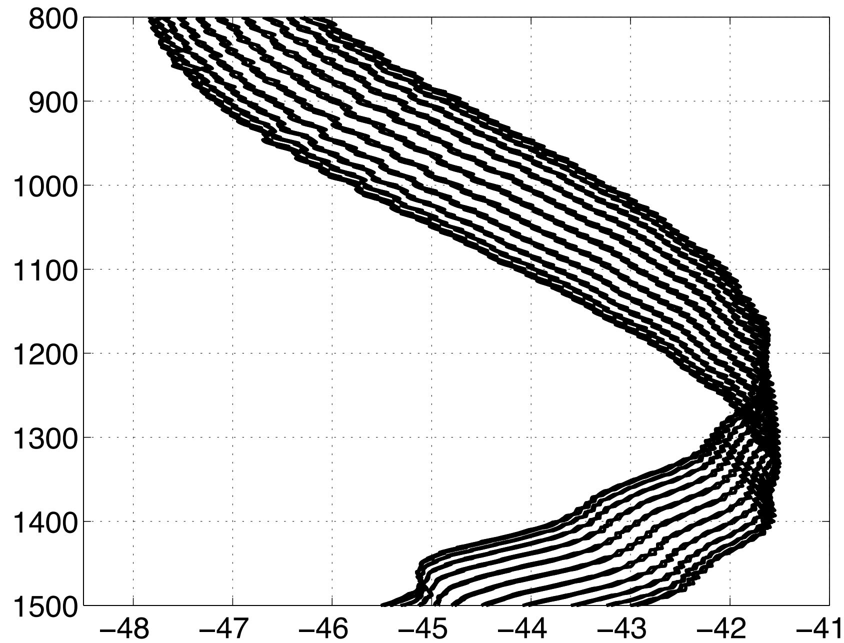

Figure 2: Time-series of intensity vs. depth predicted by the PE for profile c_4: $I_4(z,T)$, $T \in \{1, 2, 3...24\}$, simulation B3.

We will examine the results for profile c_4 in detail, but this profile is not unique in producing a depth-dependence of intensity. Figure 3 shows all the profiles used here at depths from 0m to 200m in the left panel, along with the resulting intensity vs. depth for each case in the right panel. All profiles, except the smooth, average profile, result in depth-dependence of intensity, which is translated with the evolution of the tide.

In order to answer the questions mentioned above, propagation was also calculated using a Hamiltonian ray-trace code that was developed previously by Dr. Frank Henyey. The parabolic equation (PE) is expected to contain all of the correct physics of the propagation, but what happens along the path is not revealed. When the ray-trace agrees with the PE, quantities associated with a given path that have been output all along the path then allow interpretation of the PE result.

For example, Figure 4 shows the ray intensity vs. depth for ID-3 in profile 4 in the left panel. The dashed line shows the intensity vs. depth for the smooth, average profile c_0. The right panel shows the third caustic for ID-3, which lies six km beyond the range of the DVLA. The “circle” marker shows the ray with the local maximum in intensity in the left panel, and the range and depth of that same ray at the deeper of the two cusps in the triplication in the right panel. Thus, the local maximum in intensity is associated with a cusp in the third caustic. There is no such triplication—and no local maximum in intensity—when profile c_0 is the background sound speed.

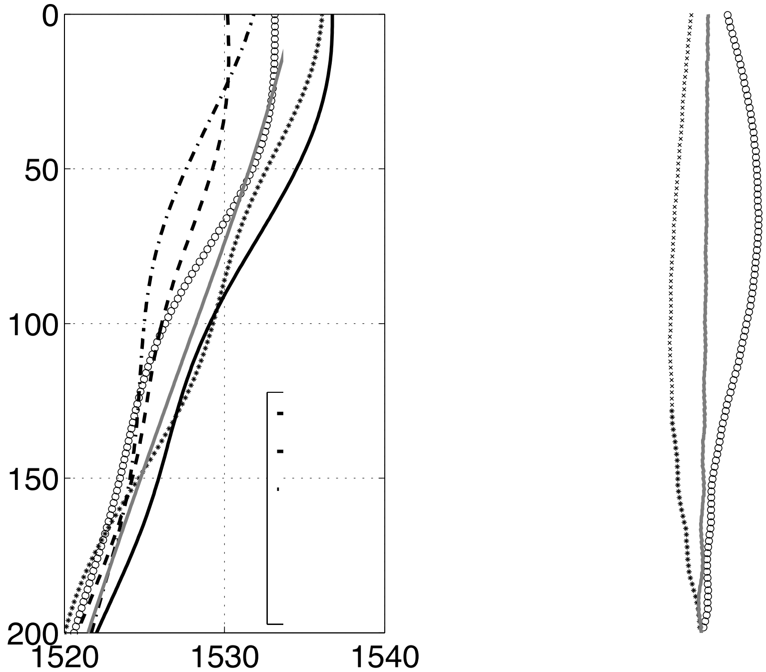

Figure 3: Left panel: Shallowest 200m of selected sound-speed profiles used as the range-independent background in IT simulations. Profile 0 is the smooth, average profile used in MCPE calculations in White et. al. 2013. The other profiles were low-pass filtered to remove scales smaller than 100m. Right panel: Intensity vs. depth shown from 800m to 1500m.

Figure 5 shows the changes in the position of the UTP of the ray with initial angle θ0 that occur with the evolution of the internal tide through times T ∈{1, 2, 3...24}, in simulations B1 and B2 (RI and RD cases, respectively).

In the RI case, the UTP moves back and forth along a curve. In the RD case, the UTP traces out an ellipse. The same is true for the triplication discussed above: in the RD case, the cusp associated with the local intensity maximum traces out an ellipse with a maximum horizontal displacement of approximately 508 m, and a maximum vertical displacement of about 22 m. In the RI case, the maximum displacements are roughly the same, but the cusp translates back and forth along a curve.

In the RI case that is shown in the bottom panel of Figure 6, the endpoints of the curve along which the UTP translates are UTPs of the rays with extrema in arrival depth. These same rays are also those with maximum or minimum turning-loop-distance. Here, we have made a connection between vertical displacement of arrival depth and turning-loop-distance.

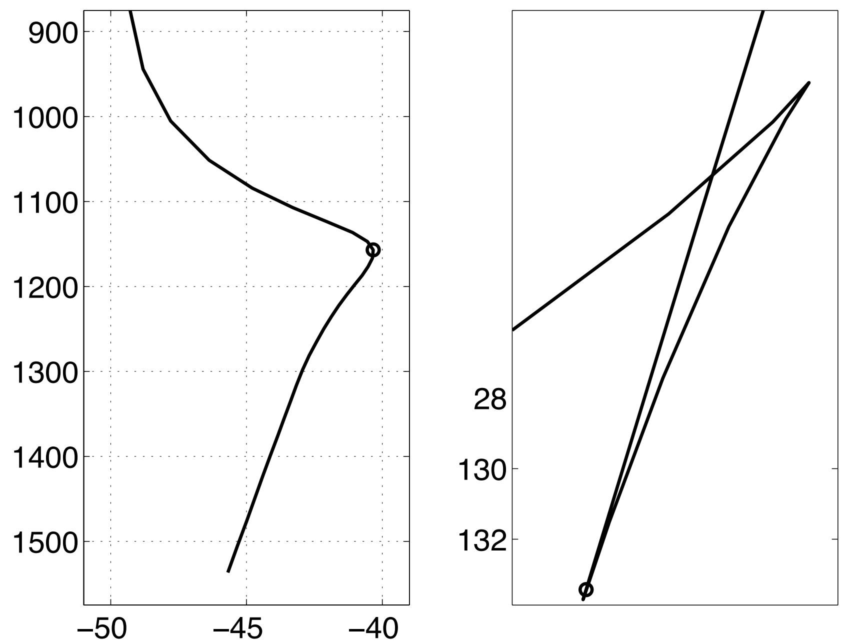

Figure 4: Intensity vs. depth at the range of reception (left panel) and range of the third caustic vs. depth (right panel) for path ID-3. This third caustic lies just beyond the reception range of 106,601 m. In the left panel, the dashed line shows the result for ID-3 with profile c_0 as the background, while the solid curve is the result for profile c_4, simulation B1, T = 1. The third caustic with profile c_0 has no triplication, and is not shown here. The black circle in both panels is the intensity (left panel) or caustic position (right panel) for the ray leaving the source at angle θ_0.

The mode-one displacement at the diurnal frequency (the mode is essentially the same at semi-diurnal frequency) has non-zero amplitude over the whole water column. The greatest amount of straining occurs above the sound-speed axis–though there is a smaller strain of the opposite sign below the axis, as seen in the right-hand panel of Figure 4. The total effect of this straining is to cause the average over depth of $|\partial_z S|$ to change sinusoidally with the phase of the tide. When the average $|\partial_z S|$ is reduced (increased), the average slope of the ray is also reduced (increased). If we consider a ray with some initial angle, but a reduced average slope, we see that the turning-loop-distance is increased. For a receiver at a fixed range, this means that a range is reached at a different point along the ray's trajectory, and therefore at a different depth—causing the vertical translation. The relationship is shown in Figure 6 for simulation B1, the RI case.

It was also found from one of the equations in the Hamiltonian formulation that the rate of change with range of ray spreading for perturbations to the initial angle (ray intensity is proportional to the perturbation in vertical distance between the rays for small changes in initial angle) is dominated by a term containing the second derivative with respect to depth of the slowness. The ray with the local maximum intensity is displaced along with a contour of the second derivative with depth of the slowness at the UTP.

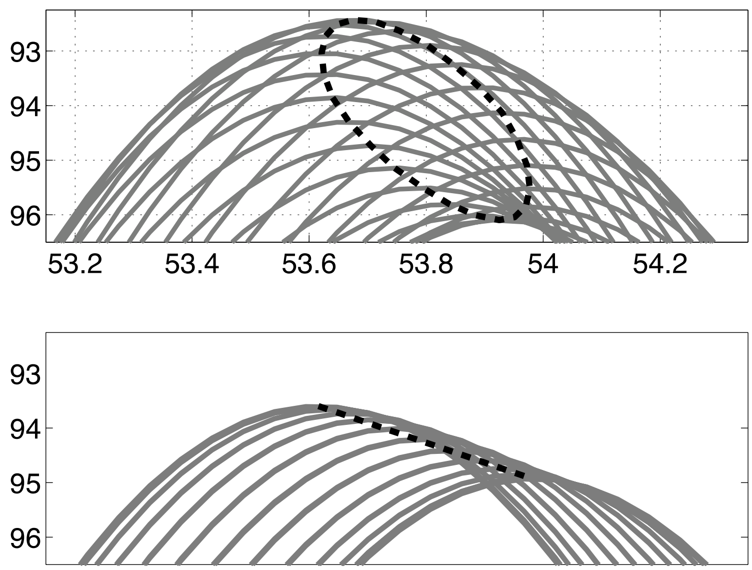

Figure 5: Evolution of the range and depth of UTP for ray ID-3 with initial angle θ_0. Each curve shows the UTP of the ray with initial angle θ_0 after propagation through a different sound-speed environment, at times $T \in \{1, 2, 3...24\}$. The top panel: RD case (simulation B2); bottom panel: RI case (simulation B1). The dashed curves pass through the UTPs at successive times to illustrate the time-order.

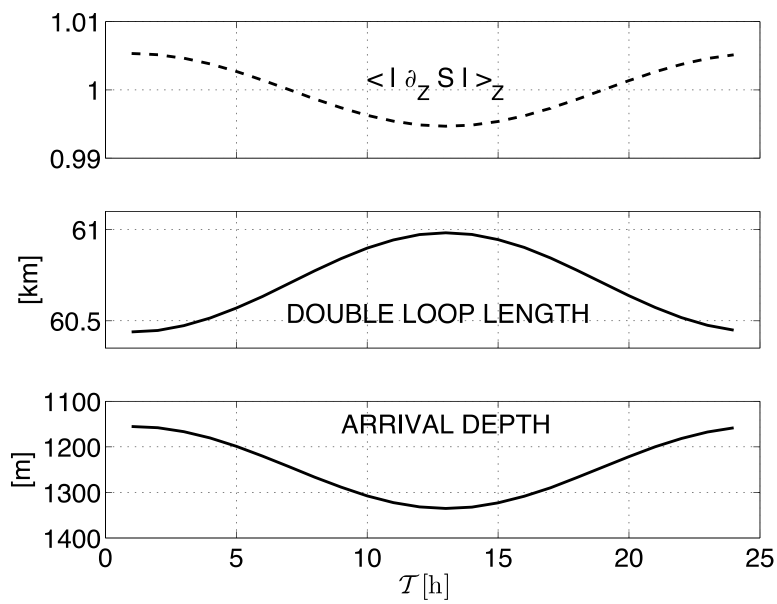

Figure 6. Top panel: Average over depth of the magnitude of the derivative of the slowness S (S = 1/c) with respect to depth vs. time–normalized by the same average over depth for the unperturbed profile. Middle panel: Double-loop distance in km for a ray with initial angle θ_0 vs. time. Bottom panel: Arrival depth of the ray with initial angle θ_0 vs. time.

Dr. White presented the results of the IT simulations and some 2010 MCPE-data comparisons in two talks at the 2014 Philippine Sea Data Workshop. The titles of the two talks were, “Preliminary comparison of MCPE to PhilSea10 measurements for scintillation index”, and, “The effect of the internal tide’s first mode on acoustic intensity in PhilSea09”.

II. New Results Award Number N00014-14-1-0218

New results for this grant have focused on co-authoring journal publications. Five manuscripts are in various stages of completion. Four of the papers address data from the Philippine Sea Experiment and the fifth is based on data from the Long-range Ocean Acoustics Experiment (LOAPEX) [1]. The titles and status of these manuscripts are provided below in the Publications Section.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D’Spain (MPL).

PUBLICATIONS

White, Andrew W, Frank S. Henyey, Rex K. Andrew, James A. Mercer, Peter F. Worcester, and Matthew A. Dzieciuch, John A. Colosi, “The effect of the internal tide’s first mode on acoustic intensity in PhilSea09”, 2014 PhilSea Data Workshop, Anza Borrego, CA

White, Andrew W., Andrew A. Ganse, Rex K. Andrew, James A. Mercer, Peter F. Worcester,

Matthew A. Dzieciuch, John A. Colosi, “Preliminary comparison of MCPE to PhilSea10 measurements for scintillation index”, 2014 PhilSea Data Workshop, Anza Borrego, CA

Chandrayadula, Tarun K., Kathleen E. Wage, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe, "Mode tomography using signals measured during the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX)," submitted to JASA.

White, Andrew W., Frank S. Henyey, Rex K. Andrew, and James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, "How the internal tide could cause intensity fluctuations," in preparation.

Andrew, Rex K., Andrew W. White, and James A. Mercer, "A test of deep water Rytov theory at 284 Hz and 107 km in the Philippine Sea," JASA, in press

Ganse, Andrew A., Rex K. Andrew, Frank S. Henyey, James A. Mercer, Peter F. Worcester, and Matthew A. Dzieciuch, "Deep fades without destructive interference in the Philippine Sea long-range ocean acoustic experiment," in preparation

Andrew, Rex K., Andrew Ganse, Andrew W. White, James A. Mercer, Matthew A. Dzieciuch, and Peter F. Worcester, "Low-frequency pulse propagation over 509 km in the Philippine Sea: A comparison of observed and theoretical pulse spreading.

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1. Andrew W. White, Rex K. Andrew, James A. Mercer, Frank S. Henyey, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, “How the internal tide could cause intensity fluctuations”
(sent to co-authors, intended for publication in JASA)

2. Andrew W. White, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, “Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: observations and modeling”, J. Acoust. Soc. Am. 134, 3347 (2013).

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North Pacific Acoustic Laboratory and Deep Water Acoustics

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Award Number N00014-13-1-0053
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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) and Deep Water Acoustics programs at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of this research is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory and Deep Water Acoustics research are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. ***The North Pacific Ambient Noise Laboratory***, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of legacy SOSUS hydrophone receivers in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory.

The second avenue includes highly focused, comparatively short-term experiments.
We have completed a pilot study/engineering test and an experiment in the ***Philippine Sea*** called **PhilSea9** and **PhilSea10**, respectively [1]. See Figure 1. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the Distributed Vertical Line Array (DVLA) from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT).

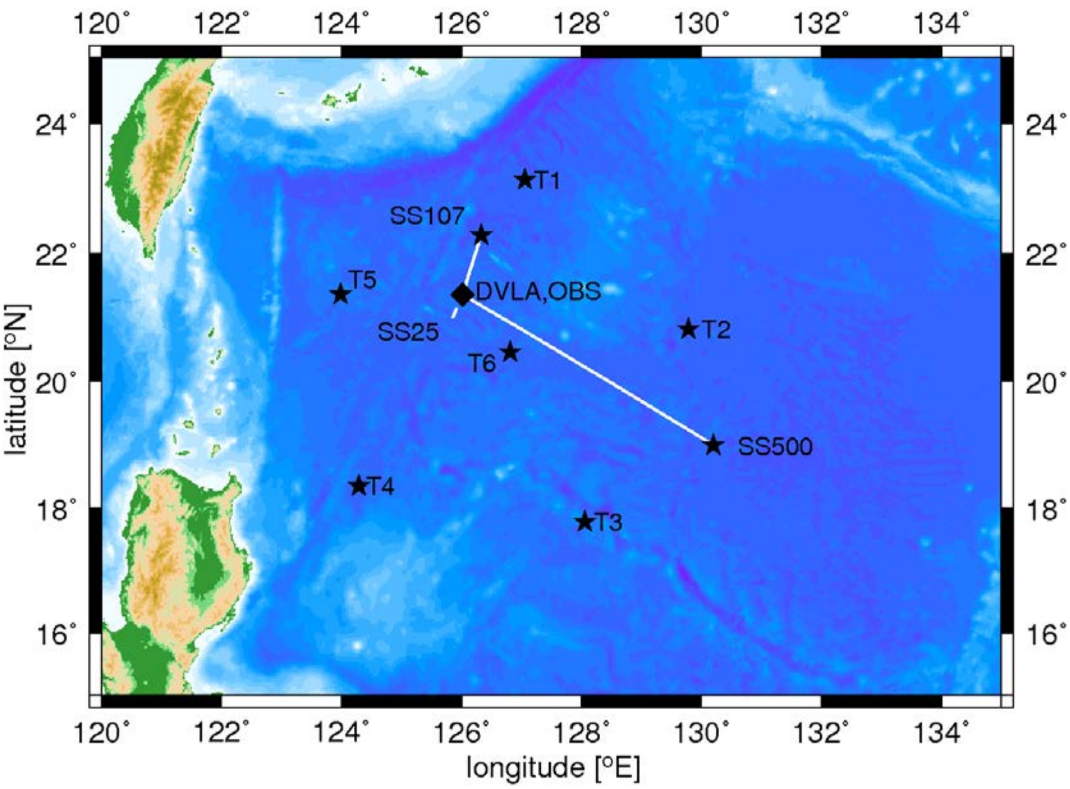

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

I. Award Number N00014-08-1-0843

The PI's work on this grant was for the most part competed at the end of FY2013. Carry over funds amounting to approximately 2.5% of the total funding were extended to FY2014. The primary work with these funds was guidance and support to Andrew White as a new Post Doc.

In addition work was completed at the Barbers Point shore termination station, the Kauai transmitter station, and collaborative efforts with Gerald D'Spain at the Marine Physical Laboratory.

Due to the transfer of property from the US Navy to the State of Hawaii the Barbers Point shore termination station was closed. The contents of the station were removed and taken to the University of Hawaii Marine Facility. Most of the hardware was eventually scrapped but some was retained by the Marine Facility for future projects.

It was noticed in October 2014 that communications between APL-UW and the Kauai transmitter station had ceased. It was determined that the microprocessor responsible for selecting various hardware channels at the site had failed. A new microprocessor was installed and communications providing periodic hardware status have resumed. Transmissions from this site are no longer executed.

A collaboration with Gerald D'Spain at the Marine Physical Laboratory (MPL) has continued. Data from PhilSea10 during the Drift Test have corrected for Doppler shift, processed and provided to MPL. The collaboration will continue as the analysis progresses.

II. Award Number N00014-13-1-0053

In his two-year post-doctoral research proposal, Dr. White proposed to explore the possible roles of internal tides, surface mixed layers, and range-dependence in acoustic fluctuations that were measured during the PhilSea09 and PhilSea10 experimental efforts. He also proposed to process the PhilSea10 data. Completion of his doctoral degree delayed the start of the post-doctoral work until September 2013. In the intervening time, Dr. Rex Andrew's group had begun processing of the 2010 500 km data. Dr. White has collaborated closely with Dr. Andrew's group, and it was therefore decided that while the group processed the data, Dr. White would design and perform Monte Carlo Parabolic Equation (MCPE) simulations to be compared with the measured acoustic propagation data. Progress made thus far under the post-doctoral proposal has included analysis of a subset of the Conductivity-Temperature-Depth (CTD) measurements made at the Distributed Vertical Line Array (DVLA); design, construction, and completion of the broadband, 500-km-range MCPE simulations for center frequencies of 200, 300, and 81 Hz; and modeling of propagation through internal-tide perturbed environments involving background sound speed profiles both with and without near-surface mixed layers. More detailed descriptions of these efforts are below.

III. Award Number N00014-14-1-0218

This award provided guidance and technical support for Andrew White in his Post Doc efforts.

NEW RESULTS

I. Award Number N00014-08-1-0843 and Award Number N00014-14-1-0218

New results for these awards are recorded in New Results Section II.

II. Award Number N00014-13-1-0053

Internal Tide Simulations

Simulated internal-tide-perturbed sound speed environments were constructed for the purpose of exploring the possible variability in acoustic intensity that may be introduced by the tides. The environmental models consisted of plane waves traveling due East; the model included only the first vertical eigenmode associated with the frequency of the diurnal tide. The first mode for the semidiurnal frequency is essentially the same as that for the diurnal, so some of the conclusions of the study will apply to both diurnal and semidiurnal tides. The difference between the tides at these two frequencies is in the range-dependence: the horizontal wave number for the diurnal tide is less than half that of the semidiurnal tide.

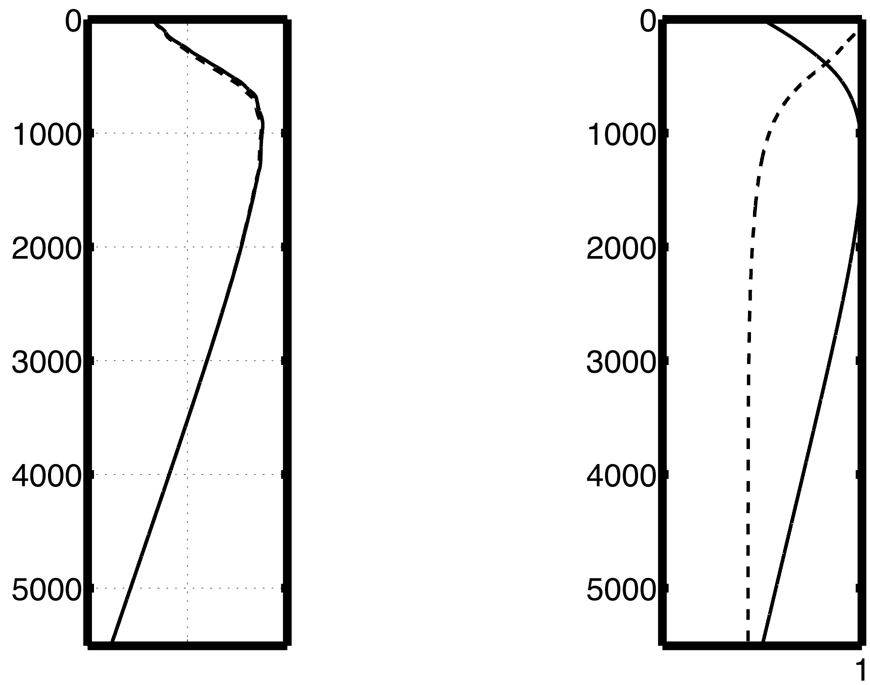

Figure 2. The slowness profile in the simulated internal-tide perturbed ocean at times that are 12 hours apart are shown in the left and middle panels; the middle panel is the same as the left, except that only depths down to 1400 m are shown. The first vertical displacement mode at tidal frequency is shown by the solid curve, and its derivative with respect to depth-the strain-shown by the dashed curve, appear in the panel at the right.

The first vertical mode is shown in figure 2, along with its vertical derivative (the strain) and with one of the sound speed slowness profiles used in this work. The slowness is shown at times that are 180 degrees apart in the tidal phase. The mode at this frequency causes a displacement of the same sign at all depths; the displacement is greatest near 1200 m depth, and decreases toward the ocean surface and toward the ocean bottom. The strain profile shows that the greatest strain occurs in the upper ocean, and then has the opposite sign at depths deeper than about 1200 m. The effect of this straining of the sound speed slowness profile is to decrease or increase, on average over depth, the first derivative with depth of the profile, with the greatest change occurring in the upper ocean.

The presence of mesoscale variability at the location of the PhilSea09 pilot study was seen in SSH measurements and corroborated with the CTD time series recorded by the CTD instruments on the DVLA [2]. Single profiles were low-pass filtered in the vertical to include only scales larger than 100 m, and then used as representative range-independent background profiles to be perturbed by the internal tides in this study. Comparison of results between the different profiles provides information about the uncertainties caused by a limited knowledge of the background sound speed.

Broadband propagation through perturbed range-depth ocean slices was calculated using the Navy Standard Parabolic Equation (NSPE) code. The arrival corresponding to ray path ID-3 was windowed out from the resulting time fronts. This path exhibited intensity fades of 10 dB that lasted 18 and 12 h, respectively, in measurements obtained during PhilSea09 [2, 3]. An example of the simulated intensity profile vs. depth for path ID-3 at 1-h intervals spanning 24 h is shown in figure 3. Variability in intensity at a given depth is predicted to occur due to the mode-1 displacement of the slowness profile.

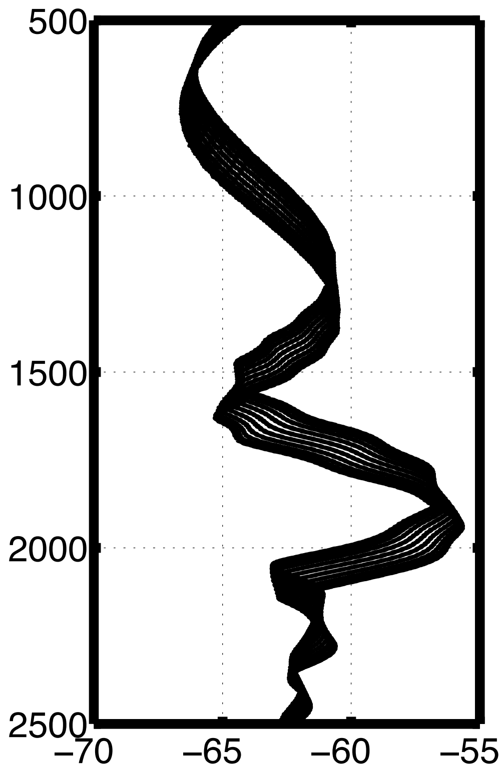

Figure 2. Intensity profiles calculated by the NSPE during the evolution of the mode-1 internal tide. The right panel is the same as the left panel, except that only depths from 800 to 1400 m are shown. Each curve is the intensity vs. depth at times separated by one hour; times spanning one diurnal tidal cycle (24 h) is shown here.

Propagation was then also calculated using a Hamiltonian ray-trace code that was developed previously by Dr. Frank Henyey. The parabolic equation (PE) is expected to contain all of the correct physics of the propagation, but what happens to the sound along its path is not revealed. When the ray-trace agrees with the PE, quantities associated with a given path that have been output all along the path then allow interpretation of the PE result.

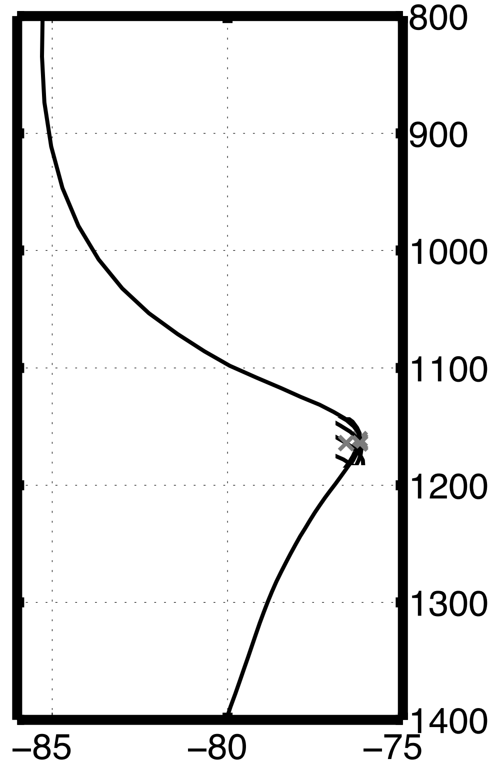

Figure 4. Intensity profiles calculated using Hamiltonian ray-tracing. The right panel is the same as the left, except that only depths from 800 to 1400 m are shown. The diamond-shaped symbols show the arrival depth and corresponding intensity of rays with the same initial angle, as the tide evolved.

The ray calculation does not capture all features of the intensity profile (see figure 4)—which is to be expected due to the infinite-frequency assumption inherent in a ray model. The high-intensity values at depths near 2000 m are due to a surface bounce. This study focuses on the rays composing the reasonably well-modeled local maximum in intensity around 1200 m.

It seems clear that the mode-1 internal tide causes the depth-dependence of the intensity to translate in the vertical while mostly retaining its shape in both the PE and ray calculations. Why is this the case? Analysis employing the Hamiltonian ray-tracing model provides some answers to this question, and leads to a deeper understanding of the effect of the internal tide on the acoustic intensity.

It is seen from the ray equations in the Hamiltonian formulation that the ray slope depends on the first vertical derivative of the slowness. The change in the average first derivative of the slowness caused by the straining of the internal tide causes a ray with a given initial angle to have a change in the average magnitude of its slope; the ray therefore arrives at a different depth at the end range.

It was also found from one of the equations in the Hamiltonian formulation that the rate of change with range of ray spreading for perturbations to the initial angle (ray intensity is proportional to the perturbation in vertical distance between the rays for small changes in initial angle) is dominated by a term containing the second derivative with respect to depth of the slowness. The turning depth of the rays is changed little by the internal tide displacement, meaning that the rays with the same initial angle turn through roughly the same slowness features at their Upper Turning Point (UTP) depth (which affects the intensity associated with the ray via the slowness' second derivative) throughout the tidal cycle. Thus the intensity associated with a ray with a given initial angle is expected to change little, while the depth-of-arrival at the end range changes significantly. These effects result in a vertical translation of the depth-dependence of the intensity profile, as seen in figures 3 and 4.

Dr. White has begun preparation of a manuscript that will present the work described above.

MCPE simulations

Displacements were computed from the CTD records for a month-long period of time, which included the time that the APL acoustic transmissions were made. Spectra were computed from these time series of displacement. The integral over the spectrum is equal to the variance of the displacement; this variance was used to determine the appropriate "GM strength ratio" [3, 4] to be used in the MCPE simulations. The strength ratio was found to be approximately 0.9—compared to the value of 1.6 as found from the same method for a similar time-period in 2009.

Dr. White performed a total of 240 broadband MCPE calculations (each, for three center frequencies of 81, 200, and 300 Hz) on a computer cluster, each through an independent realization of an internal-wave perturbed ocean. Arrivals corresponding to unique paths were windowed from the resulting time fronts. The arrivals and the depths at which they were extracted from the simulated time fronts are shown in figure 5. An undergraduate student who was working for Dr. Rex Andrew's group was tasked with organizing these windowed simulated arrivals into a database. Dr. Andrew's group also had the student create a corresponding database (for the 200 Hz signal, thus far) that was populated with arrivals measured during PhilSea10. The MCPE-simulated and the experimentally-measured databases will be shared between Dr. Andrew's group and Dr. White, facilitating various comparisons between MCPE and measurements.

COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain (MPL).

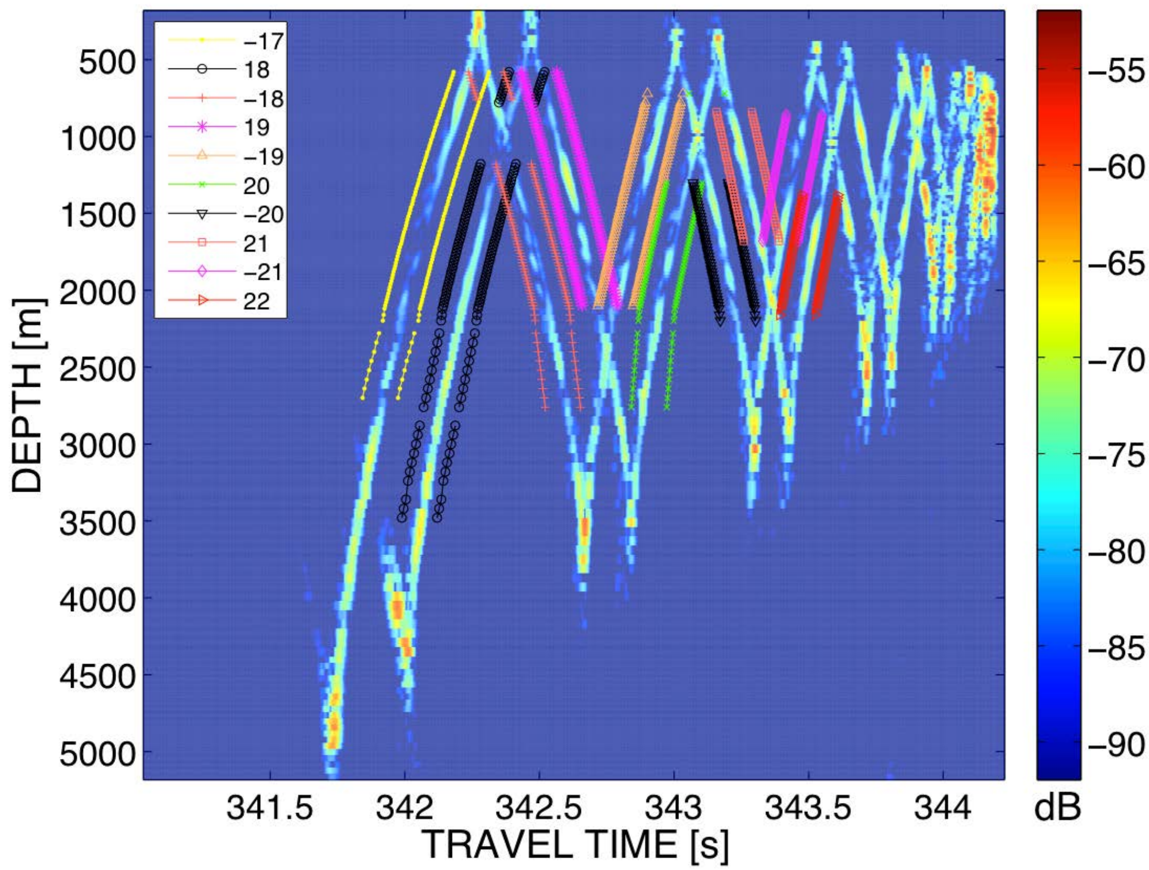

Figure 5. An example of the MCPE timefronts, including windows used to extract particular paths (associated with ID labels that are shown in the legend) from the simulated data. The simulated data was windowed only at the depths for which there are available measured data for comparison.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

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[3] Andrew W. White, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, "Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: observations and modeling", J. Acoust. Soc. Am., **134**, 3347, 2013.

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PUBLICATIONS

Andrew W. White, Frank S. Henyey, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi "Acoustic intensity fluctuations and internal tides: An unexpected connection." *J. Acoust. Soc. Am.*, submitted.

Rex K. Andrew, Andrew Ganse, Andrew W. White, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi "Low-Frequency Pulse Propagation over 510 km in the Philippine Sea: A Comparison of Observed and Theoretical Pulse Spreading" *J. Acoust. Soc. Am.*, in press

Frank S. Henyey, James A. Mercer, Rex K. Andrew, and Andrew W. White "A Method to Determine Small-Scale Internal Wave and Spice Fields from a Single CTD Profile with Application to Three Long-Range Ocean Acoustics Experiments" APL-UW TM 1-14, Applied Physics Laboratory, University of Washington, March 2014

CONFERENCE PRESENTATIONS

Andrew W. White, Frank S. Henyey, Rex K. Andrew, James A. Mercer, Peter F. Worcester, and Matthew A. Dzieciuch, John A. Colosi, "The effect of the internal tide's first mode on acoustic intensity in PhilSea09", 2014 NPAL Workshop, Anza Borrego, CA

Andrew W. White, Andrew A. Ganse, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, John A. Colosi, "Preliminary comparison of MCPE to PhilSea10 measurements for scintillation index", 2014 NPAL Workshop, Anza Borrego, CA

Andrew W. White, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, John A. Colosi, "Intensity statistics for low-frequency acoustic transmissions in the Philippine Sea", 2013 Joint Undersea Warfare Technology Fall Conference, Groton, CT, USA

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14. ABSTRACT
A mechanism is presented by which the observed acoustic intensity is made to vary due to changes in the acoustic path that are caused by internal-tide vertical fluid displacements. The position in range and depth of large-scale caustic structure is determined by the background sound-speed profile. Internal tides cause a deformation of the background profile, which changes the positions of the caustic structures–introducing slow intensity changes at a fixed position in depth and range. Parabolic equation and Hamiltonian ray-tracing calculations indicate that internal tides could cause enhanced variability in the intensity in the form of slow changes. Furthermore, the calculations demonstrate how large-scale perturbations to the index of refraction can result in intensity fluctuations--contrary to conclusions of previous theoretical work.

15. SUBJECT TERMS
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