North Pacific Acoustic Laboratory and Deep Water Acoustics

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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.

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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).

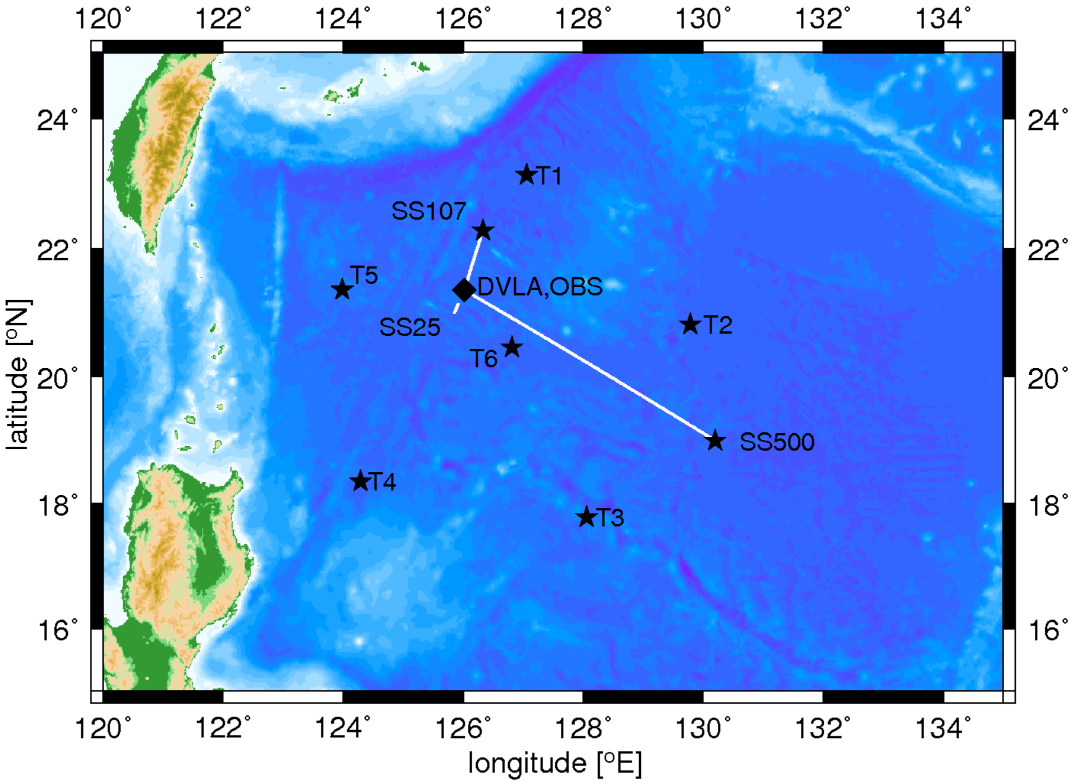

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

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.

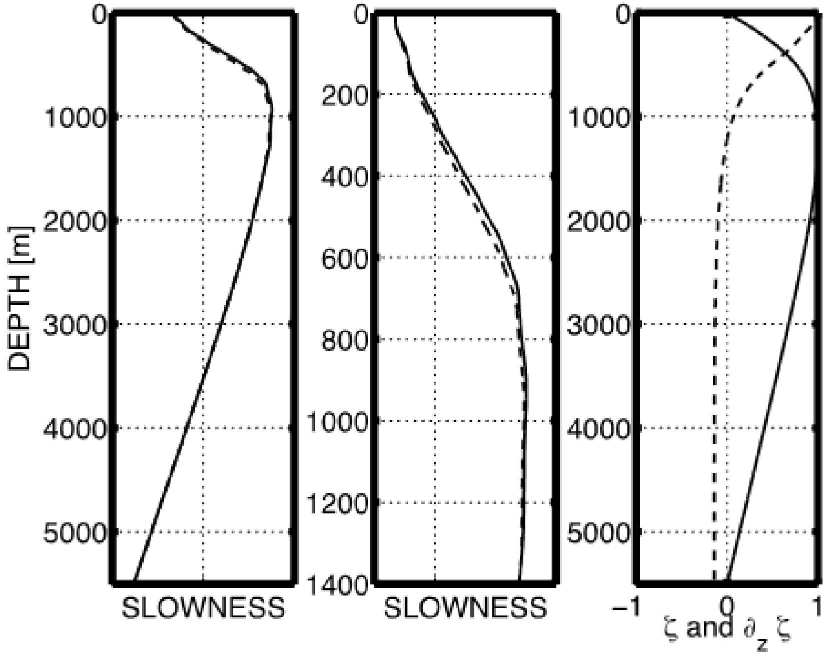

Figure 2. The slowness profile in the simulated internal-tide perturbed ocean at times that are 12 hours apart are shown in the left and middle panels; the middle panel is the same as the left, except that only depths down to 1400 m are shown. The first vertical displacement mode at tidal frequency is 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.

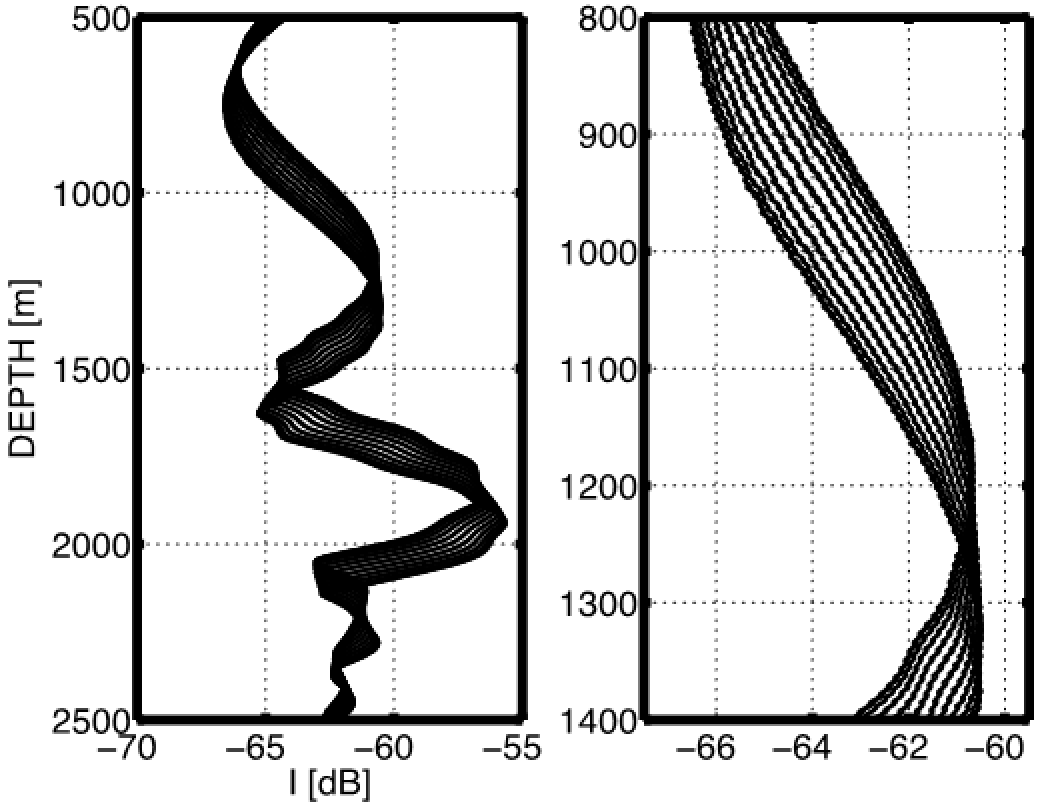

Figure 2. Intensity profiles calculated by the NSPE during the evolution of the mode-1 internal tide. The right panel is the same as the left panel, except that only depths from 800 to 1400 m are shown. Each curve is the intensity vs. depth at times separated by one hour; times spanning one diurnal tidal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

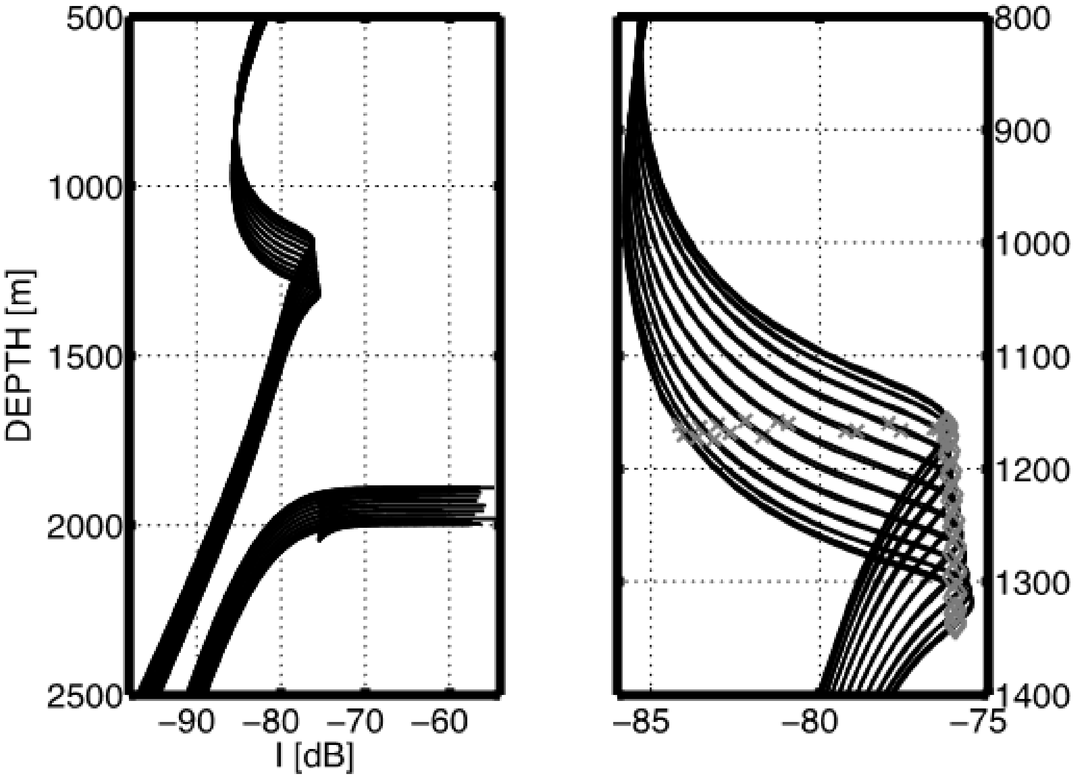

Figure 4. Intensity profiles calculated using Hamiltonian ray-tracing. The right panel is the same as the left, except that only depths from 800 to 1400 m are shown. The diamond-shaped symbols show the arrival depth and corresponding intensity of rays with the same initial angle, as the tide evolved.

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).

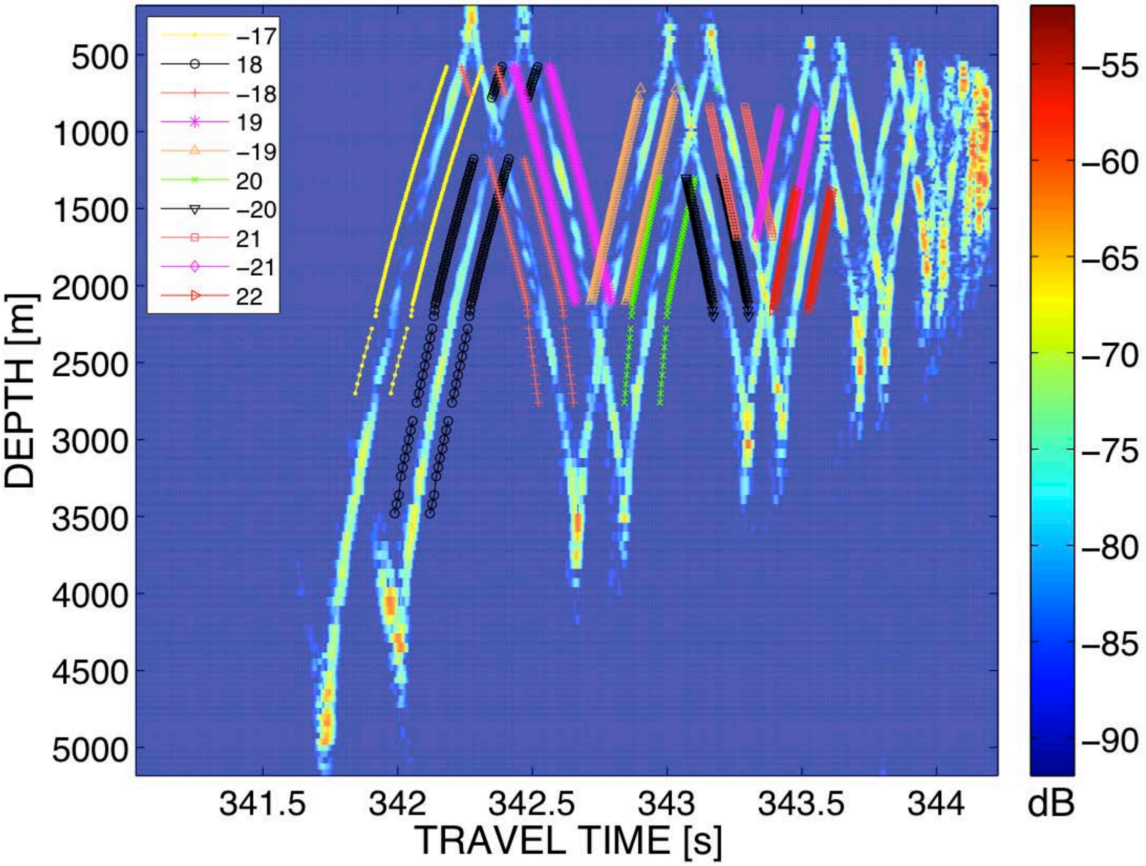

Figure 5. An example of the MCPE timefronts, including windows used to extract particular paths (associated with ID labels that are shown in the legend) from the simulated data. The simulated data was windowed only at the depths for which there are available measured data for comparison.

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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