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Subj: ONR Grant# N00014-18-1-2219, "Comprehensive Data Analysis and Modeling of Mid and Low Frequency Sonar in Coastal and Basin-Scale Environments"

Encl: (1) Final Technical Report for Subject Grant
(2) ASA Publication "Trends in low-frequency underwater noise off the Oregon coast and impacts of COVID-19 pandemic."
(3) IEEE Publication "Range-Dependent Inversion for Seabed Parameters Using Vector Acoustic Measurements of Underwater Ship Noise."
(4) ASA Publication "Physical effects of sound exposure from underwater explosions on Pacific sardines (*Sardinops sagax*)."
(5) ASA Publication "Estimation of seabed properties and range from vector acoustic observations of underwater ship noise."
(6) IEEE Publication "Vector Acoustics Analysis of Time-Separated Modal Arrivals From Explosive Sound Sources During the 2017 Seabed Characterization Experiment."
(7) UACE 2019 Conference "Efficient Modeling of 3D Acoustics Paths to Improve Source Triangulation."
(8) ASA Publication "Source triangulation utilizing three-dimensional arrivals: Application to the search for the ARA San Juan submarine."
(9) SF298 for Enclosure

Enclosure (1) is the Final Technical Report for the subject grant along with 7 presented works (2,3,4,5,6,7,8). Enclosure (9) is the SF 298 form. These documents constitute the Final Technical Report and deliverable for ONR Grant# N00014-18-1-2219.

cc: Grant & Contract Administrator, APL-UW
Office of Sponsor Programs, UW
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COMPREHENSIVE DATA ANALYSIS AND MODELING OF MID AND LOW FREQUENCY SONAR IN COASTAL AND BASIN-SCALE ENVIRONMENTS

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19 January 2022

**Final Report
Award Number N00014-18-1-2219**

The technical works and presentations listed here cover research completed between 15 March 2018 and 30 September 2021, funded by the ONR grant entitled: “Comprehensive Data Analysis and Modeling of Mid and Low Frequency Sonar in Coastal and Basin-Scale Environments.”

The primary objective of this ONR grant is improving the understanding of acoustic propagation on two scales, $O(10\text{ km})$ littoral scale and $O(1000\text{ km})$ basin scale. To accomplish this goal, two tasks were undertaken simultaneously. One task was curating a set of acoustic and oceanographic measurements, including broadband, mid- and low-frequency sources as well as ambient noise. The other task was the development of a model-framework capable of modeling 3D aspects of the ocean acoustic propagation. The two tasks are complimentary in that data validates the model, while the model provides a tool to examine the effects of the ocean environment on sound propagation.

The model-framework is built as a Matlab module which facilitates one set of user defined input for multiple propagation models, both code developed under this grant and standard propagation models. The key element of the model-framework which allows for 3D propagation is reducing the dimension by decomposing the depth component of propagation into acoustic modes. Several mode-finding routines are available to populate a grid of mode properties based on the local oceanography, bathymetry and sediment structure. Standard 2D propagation methods (including rays, modes or the parabolic equation) are then used on a longitude and latitude grid to model 3D effects, including bathymetric and oceanic refraction. A core feature of the model-framework is the vector field output which facilitates comparative studies to vector field measurements, including those collected by the Intensity Vector Autonomous Recorder (IVAR) system deployed during three ONR- funded experiments.

Over the course of this grant, many advances were made through model/data comparison and analysis. Acoustic data that supports the propagation modeling effort and validation stems primarily from ONR funded field experiments, but also includes and low-frequency data from ocean observatories. These valuable datasets are discussed in the annual reports, and several are published in referred journals. Data and code developed under the grant is maintained by the investigator, and available for use in future analysis and model development.

Below lists several refereed published studies completed under this grant or partially supported by it. Of these, we highlight three studies as representative of the primary technical output from this grant and a copies of these associated works are attached.

The first study, entitled “Source triangulation utilizing three-dimensional arrivals: Application to the search for the ARA San Juan submarine” (2019), outlines the objective of the 3D model framework. It is worth noting that this analysis was done contemporaneously with an active search for the ARA San Juan submarine, and the analysis helped reduce the error in acoustic localization that led to its discovery. A follow-on conference proceedings paper, “Efficient Modeling of 3D Acoustic Paths to Improve Source Triangulation (2019),” demonstrates how the hybrid model approach can improve efficiency in long-range acoustic propagation modeling, implementing a nested-model using ray theory to bypass the computationally expensive full-field numerical PE computation over 8000 km domain. Another welcome result of this work was the development of code and expertise to access and process the publically available data from ocean acoustic observatories which has facilitated global ambient noise studies.

The second study, entitled “Trends in low-frequency underwater noise off the Oregon coast and impacts of the COVID-19 pandemic” (2021), is an example of global noise study motivated by the emergence of Covid-19. This detailed analysis of 6 years of underwater noise collected by the Regional Cabled Array (RCA) ocean observatory reveals a subtle, but clearly discernable, influence of reduced shipping noise owing to scaled back economic activity caused by the worldwide COVID-19 epidemic. As part of this work, the extremely large dataset of Automatic Information System (AIS) messages was processed to estimate shipping density in the Pacific Northeast. Perhaps what was most enlightening is how shipping noise levels are linked to seasonal variation of near-surface water temperature. This effect was confirmed within the model-framework, which with the time-history of oceanographic data from the RCA and AIS data as input predicts the noise levels over the 6 year study period. This study emphasizes the importance of seasonal oceanography on ambient noise levels, and in particular how downward refraction impacts long-range propagation of sound generated at the surface.

The third study, entitled “Range-dependent inversion for seabed parameters using vector acoustic measurements of underwater ship noise” (2021), demonstrates the model-framework application to littoral scales using vector acoustic noise data collected during the SBCEX17 experiment. In this study, the model-framework reproduces the distinct vector signature of a passing commercial ship relating to multi-mode interference. The model framework is implemented as an inversion tool to estimate the range varying thickness of the mud layer, and its corresponding geoacoustic properties. Results of this study are consistent with an extensive seismic survey of the area, and emphasize how noise sources of opportunity provide enough vector information to identify critical elements of the environment affecting propagation.

**Technical Articles based on research funded by Office of Naval Research Grant
N00014-18-1-2219 for period March 2018-September 2021**

Refereed Publications

1. P. H. Dahl, D. R. Dall'Osto, and M. J. Harrington, Trends in low-frequency underwater noise off the Oregon coast and impacts of the COVID-19 pandemic, *J. Acoust. Soc. Am.*, 149, 4073-4077, June 2021.
2. P. H. Dahl and D.R. Dall'Osto, Range-dependent inversion for seabed parameters using vector acoustic measurements of underwater ship noise, *IEEE J. Oceanic Engineering*, (currently online only) , DOI 10.1109/JOE.2021.3086880, June 2021.
3. P. H. Dahl, A. K. Jenkins, B. Casper, S. E. Kotecki, V. Bowman, C. Boerger, D. R. Dall'Osto, M. A. Babina, and A. N. Popper, Physical Effects of Sound Exposure from Underwater Explosions on Pacific Sardines (*Sardinops sagax*), *J. Acoust. Soc. Am.*, 139, 311-319, May 2020.
4. P. H. Dahl and D.R. Dall'Osto, Estimation of seabed properties and range from vector acoustic observations of underwater ship noise, *J. Acoust. Soc. Am.*, *Express Letters*, EL 345-350, April 2020.
5. P. H. Dahl and D.R. Dall'Osto, Vector acoustic analysis of time-separated arrivals from explosive sound sources during the 2017 Seabed Characterization Experiment, *IEEE J. Oceanic Engineering*, 45, 131-143, Jan. 2020.
6. David R. Dall'Osto, Efficient Modeling of 3D Acoustic Paths to Improve Source Triangulation, Proceedings of the European Meeting on Underwater Acoustics UACE2019 Hersonissos, Crete July 2019.
7. David R. Dall'Osto, Source triangulation utilizing three-dimensional arrivals: Application to the search for the ARA San Juan submarine, *J. Acoust. Soc. Am.* 146, 2104-2112 Sept. 2019.

Conference Presentations

1. Peter H. Dahl, Michael Harrington and David R. Dall'Osto, "Trends in low frequency ambient noise for a site 80 km off the Oregon coast over approximately four years ending August 2020," Acoustical Society of America Conference *virtual* (June 2021).
2. David R. Dall'Osto and Ross Heyburn, "On the potential of using sound sources of opportunity recorded on the Comprehensive Nuclear-Test-Ban Treaty hydroacoustic network for historical ocean thermometry," Acoustical Society of America Conference San Diego, CA (December 2019).
3. David R. Dall'Osto, "Efficient Modeling of 3D Acoustic Paths to Improve Source Triangulation", European Meeting on Underwater Acoustics UACE2019 Hersonissos, Crete (July 2019).
4. David R. Dall'Osto, "Reducing ambiguity in hydroacoustic triangulation through consideration of three-dimensional propagation features," Science and Technology conference of the CTBTO, Vienna, Austria (June 2019).
5. David R. Dall'Osto, Peter H. Dahl, W. C. Kirkpatrick Alberts and Michael V. Scanlon, "Airborne vector sensor experiments within an anechoic chamber," Acoustical Society of America Conference, Victoria , B.C. (December 2018).
6. David R. Dall'Osto, Peter H. Dahl, "Observations of resonances and anti-resonances in modal propagation over muddy sediment layer," Acoustical Society of America Conference, Victoria , B.C. (December 2018).
7. P. H. Dahl and D.R. Dall'Osto, "Pressure and particle velocity measurements from a broad band source at ranges 1-10 km," Acoustical Society of America Conference, Minneapolis, MN (May 2018).

Trends in low-frequency underwater noise off the Oregon coast and impacts of COVID-19 pandemic

Peter H. Dahl, David R. Dall'Osto and Michael J. Harrington

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Trends in low-frequency underwater noise off the Oregon coast and impacts of COVID-19 pandemic^{a)}

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ABSTRACT:

Approximately six years of underwater noise data recorded from the Regional Cabled Array network are examined to study long-term trends. The data originate from station HYS14 located 87 km offshore of Newport, OR. The results indicate that the third-octave band level centered at 63 Hz and attributable to shipping activity is reduced in the spring of 2020 by about 1.6 dB relative to the mean of the prior five years, owing to the reduced economic activity initiated by the COVID-19 pandemic. The results are subtle, as the noise reduction is less than the typical seasonal fluctuation associated with warming ocean surface temperatures in the summer that reduces mode excitation support at typical ship source depths, causing a repeated annual level change on the order of 4 dB at shipping frequencies. Seasonality of the noise contribution near 20 Hz from fin whales is also discussed. Corroboration of a COVID-19 effect on shipping noise is offered by an analysis of automatic identification system shipping data and shipping container activity for Puget Sound, over the same six-year period, which shows a reduction in the second quarter of 2020 by $\sim 19\%$ and $\sim 17\%$, respectively, relative to the mean of the prior five years.

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I. INTRODUCTION

The Ocean Observatories Initiative (OOI) Regional Cabled Array (RCA),^{1,2} funded by the National Science Foundation, provides a constant stream of data from the seafloor and water column spanning the Juan de Fuca plate. Here, we present underwater sound data recorded at the RCA site known as Hydrate Ridge station HYS14 (Fig. 1), located on the seabed at a depth of 778 m, approximately 87 km offshore of Newport, OR (44.569° N, 125.148° W). We examine long-term trends in shipping-related underwater noise and how trends compare to recent conditions that may have been impacted by the COVID-19 pandemic.

The HYS14 hydrophone commenced data streaming on 15 January 2015, and this study incorporates all data from that point until 17 August 2020, after which the primary node (PN1B) of the RCA developed a fault that took part of the RCA infrastructure offline. (Replacement of the failed node is scheduled for summer 2021.) Station HYS14 was selected for analysis primarily because there are fewer noise producing real-time measurement systems at this station relative to other stations within the RCA system. The site is well situated within north-south coastal shipping lanes (Fig. 1) and likely to experience more distant traffic noise^{3,4} associated with great-circle shipping routes connecting northwest ports (e.g., Vancouver, BC, and Seattle and Tacoma, WA) with Asian ports.

The paper is organized as follows: Sec. II describes data and processing methods in the frequency domain. Note that we use both linear and geometric averages to describe measures of central tendency in spectral and mean-square levels depending on the purpose, which will be explained. Section III provides results, including a short summary of the biophony that must be understood in the context of the noise related to shipping. Here, we also document the seasonal propagation effect for near-surface radiated shipping noise, including simple modeling that captures the trends. These two elements provide necessary background for our conclusions related to underwater noise shipping and economic impacts of COVID-19, discussed in Sec. IV and summarized in Sec. V.

II. DATA DESCRIPTION AND PROCESSING METHODS

The data were obtained through the Incorporated Research Institutions for Seismology (IRIS) network, accessing station OO, sensor HYS14. The sampling frequency is 200 Hz applied after data are low-pass filtered with a 3-dB corner frequency of about 90 Hz prior to sampling. The HYS14 hydrophone is an HTI-90-U low-frequency hydrophone manufactured by HiTech (Long Beach, MS), with effective receiving sensitivity (inclusion of gain) equal to -174 dB re V/ μ Pa.

The basic spectral analysis revolves around the sequence of whole hours for a given day as recorded in UTC, as follows. We take the fast Fourier transform (FFT) of Hanning tapered blocks equal to 12 000 points ($T = 60$ s) and average 119 adjacent blocks overlapped by 50%,

^{a)}This paper is part of a special issue on COVID-19 Pandemic Acoustic Effects.

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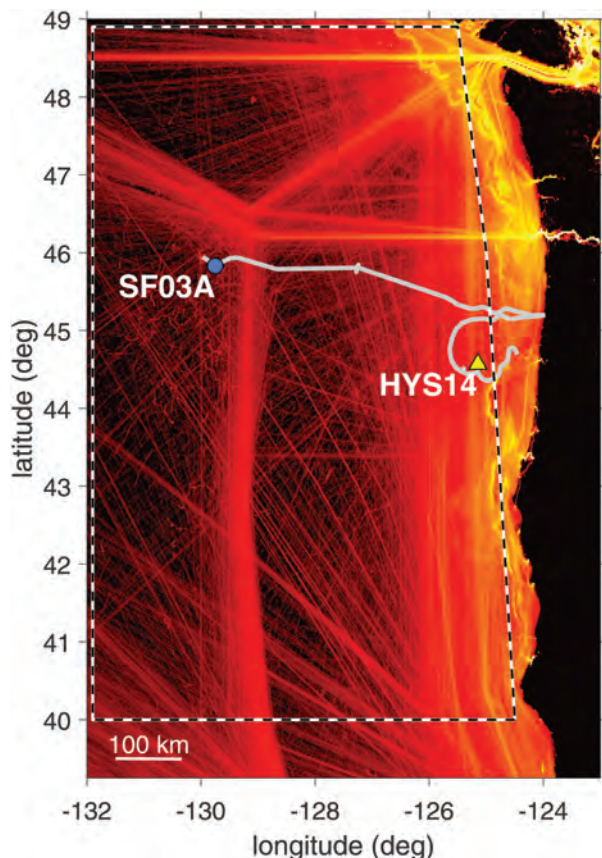


FIG. 1. (Color online) Heat map of AIS reports in the Northeast Pacific Ocean 2015–2020, location of RCA cabling (gray lines), station HYS14 (triangle), and water column measurement site SF03A (circle). The white/black dashed outline identifies the area used to quantify shipping density.

corresponding to a 1-h spectral estimate following Welch's overlapped segment average (e.g., see Percival⁵). These one-sided variance spectra $S_n(f)$ integrate to the mean-square pressure of the corresponding n th-hour non-tapered block. For a given day, the pressure variance spectrum $P_{ms}(f) = \langle S_n(f) \rangle$, in dimension Pa^2/Hz ; we also compute $P_{dB}(f)$ equal to $\langle 10 \log_{10} S_n(f) \rangle$, representing a geometric mean over the day. The geometric mean is sensitive to the time scale of the spectral estimate, and after some experimentation, 1 h, as also suggested in Ref. 6, provides the suitable balance that captures longer-term seasonal trends and mitigates the influence of transient events.

Two correlates to the acoustic data are based on direct measurements of the sound speed profile and shipping density. Sound speed is derived from measurements at RCA station SF03A, located 388 km from the HYS14 site (Fig. 1); here a winched shallow-water profiler continuously measures conductivity and temperature over the upper 200 m.

Shipping density is assessed by automatic identification system (AIS) reports⁷ distilled into a count of the number of ships with unique International Maritime Organization (IMO) numbers, limited in this study to ships >100 m length within ~600 km west, north, or south of HYS14 (within the white/black dashed line in Fig. 1).

III. RESULTS

A summary of the entire HYS14 hydrophone data set to date is displayed in the stacked image of the daily $P_{dB}(f)$ spanning the period 15 January 2015–17 August 2020 [Fig. 2(a)]. Occasional data interruptions amount to 83 missing days during this period of 5 years and 7 months. Black, dashed rectangles identify known research vessel activity occurring above the sensor (2018) and a nearby seismic survey (2019), which are removed from subsequent analysis.

A prominent seasonal feature of the data is seen in the band centered near 20 Hz, which is consistent with that produced by fin whales (*Balaenoptera physalus*).^{8,9} Examining select periods (typically hours in duration) while this signal is present, a representative coherence time scale τ_c , e.g., as defined in Ref. 10, is ~ 0.25 s, with center frequency ~ 20.5 Hz. Less prominent is a higher-frequency counterpart, between 40 and 45 Hz; this has been attributed to feeding calls by fin whales,¹¹ although generally not as contemporaneous with 20-Hz calls as observed here.

For the 20-Hz signal, it is of interest to take the daily average of $P_{ms}(f)$, integrated over the $1/\tau_c$ or the 4-Hz band, 18.5–22.5 Hz, and apply a 30-day moving (geometric) average using the decibel equivalent. Converting back to mean-square pressure, the results agree with Gaussian fits

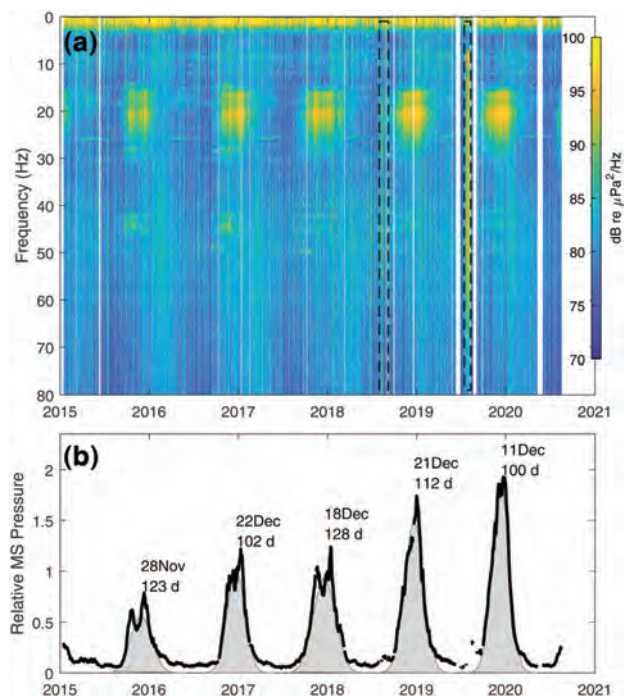


FIG. 2. (Color online) (a) Daily averaged $P_{dB}(f)$ spanning the period 15 January 2015–17 August 2020 for RCA hydrophone HYS14. Black, dashed rectangles identify research vessel activity in 2018 and a seismic survey in 2019. (b) Mean-square pressure as computed from daily averaged $P_{ms}(f)$ integrated over the 18.5–22.5 Hz band and subjected to a 30-day moving geometric average. The mean-square pressures are normalized in the plot such that 1 is mapped to a mean-square pressure equivalent to 100 dB re μPa^2 , and 2 is equivalent to 103 dB. A separate Gaussian fit is made for each year (shaded curves) with first moment date and 2σ spread in days annotated.

made for each year to describe behavioral timing, with the date of the first moment falling between 28 November and 22 December and 2σ spread ranging from 100 to 128 days [Fig. 2(b)]. To assess variation, the pre-averaged data are detrended by the moving-average result, yielding an approximately Gaussian variation that is expected¹⁰ with standard deviation ~ 2.5 dB, most applicable in the vicinity of the period of each first moment date.

The driver of this timing, for example, as in migration or enhanced call activity during breeding periods, is beyond the scope of this study, although it is noteworthy that the mean-square pressure in this band generally increases with advancing year, whereas the 2σ duration in days times mean-square pressure remains approximately constant. We also observe a narrow band tone at ~ 26 Hz during the minima in fin whale calls, suspected to be a chorus of blue whale (*Balaenoptera musculus*) calls. While individual calls are not discernible in these data, the frequency of the tone

modulates with the season and decreases at a rate of 1/8 Hz per year, consistent with other observations in the Southern Hemisphere.^{12,13}

These are rich and stand-alone investigations that are important to mention here for context. Our main focus in this study, however, is on noise from shipping, for which we limit our analysis to the third-octave (decidecadal) band spanning 56.23–70.79 Hz centered at 63.10 Hz to be sufficiently separated in frequency from this biophony. This corresponds, for example, to one of the important third-octave bands studied for long-term trends from shipping noise along the U.S. West Coast between 1996 and 2007.⁴

The daily $P_{dB}(f)$ is further averaged over this band, as this is the most effective method to characterize the seasonal pattern in the band spectral level that is linked to annual ocean surface temperature cycles, as reported by others.¹⁴ The geometric average, similar to taking the median, tends to stabilize the variance and reduces the influence of

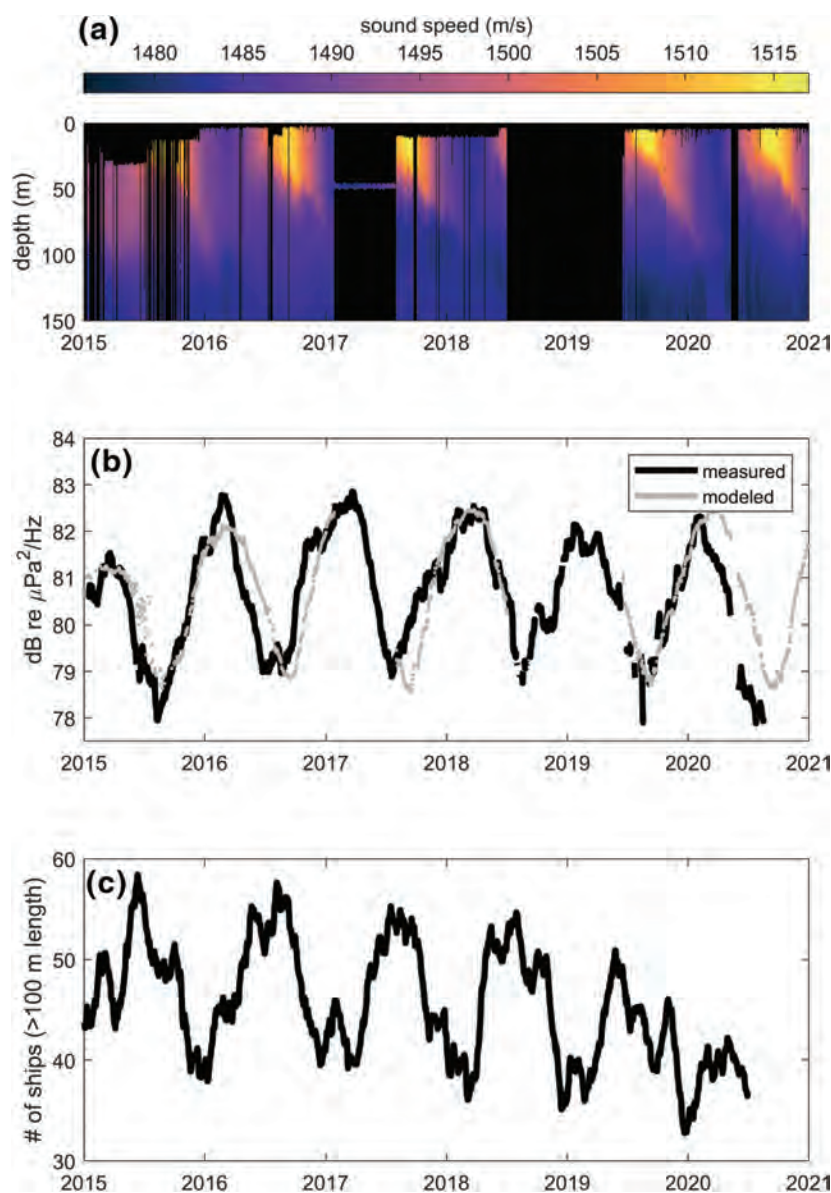


FIG. 3. (Color online) (a) Sound speed profiles measured at SF03A; black regions indicate no data. (b) Average $P_{dB}(f)$ within the 63-Hz third-octave band (black line) smoothed by a 45-day moving average and modeled levels (gray line) based on the measured sound speed profile. (c) A 45-day moving average of number of ships with length >100 m passing within the region indicated in Fig. 1, as identified by unique IMO number.

episodic high outlying values. Unlike the median, all values contribute to the average.

With seasonal warming and onset of higher ocean surface temperatures, it is expected that mode excitation support moves deeper and thus away from typical ship source depths. Evidence for this comes from converting the shallow-water profiler data from RCA station SF03A to sound speed [Fig. 3(a)], which can be used in simple modeling. A 45-day moving average of $P_{dB}(f)$ (intentionally longer than in the case of the fin whale data) is taken [black line, Fig. 3(b)], which shows a remarkable seasonal trend, and detrending yields a Gaussian variation with standard deviation ~ 2 dB. This trend is reasonably captured upon using the sound speed data [Fig. 3(a)]¹⁵ and computing an incoherent sum of modes based on mode excitation coefficients for a 60-Hz source at a notional source depth of 5 m multiplied by the respective propagation decay (imaginary part of wavenumber). The results are summed for a uniform distribution of sources from 1 to 600 km, yielding a model (not calibrated) of the seasonal pattern in band spectral level with variation [gray line in Fig. 3(b)] that is in phase with the long-term observations of shipping noise. Wind-related noise will have some influence, but less at frequencies lower than about 100 Hz.¹⁶ However, it is also not plausible for it to be manifested in such a repetitive manner over the course of six annual cycles; furthermore, wind speeds at this site are relatively constant during the year.

Referring to this now as a seasonal propagation effect for near-surface generated shipping noise, it is also evident that ship density as reflected by the daily count of vessels over 100-m length within the box in Fig. 1, is *out of phase* with the seasonal propagation effect, i.e., highest shipping activity generally occurs in mid-year [Fig. 3(c)].

These results (Fig. 3) suggest that any underlying trend in the underwater noise data associated with COVID-19 will necessarily be subtle. To examine this trend, we return to the daily (linear) $P_{ms}(f)$, taking the average over the 63-Hz third-octave band. Operating with daily $P_{ms}(f)$, as with the fin whale case (but here maintaining units of spectral density), is more appropriate given our goal to assess the addition of incoherent sources¹⁷ rather than a seasonal long-term propagation trend (Fig. 3), which uses $P_{dB}(f)$.

The 45-day moving geometric average of the 63-Hz band level is plotted with respect to Julian day for each year (Fig. 4). The seasonal dependence [Fig. 3(b)] is evident, although reduced when based on $P_{ms}(f)$ with a peak-to-trough difference of about 2–3 dB, with the 63-Hz band levels over the six years reaching an annual minimum near day 210.

It is also apparent that the level for year 2020 departs from the previous five years starting at around day 60. The departure is not large but is persistent, starting at about ~ 1 dB and increasing to ~ 2 dB. This result is notionally consistent with recent results obtained from the Canadian network north of our study site.¹⁸ Grouping the data from the prior five years and computing the mean and standard

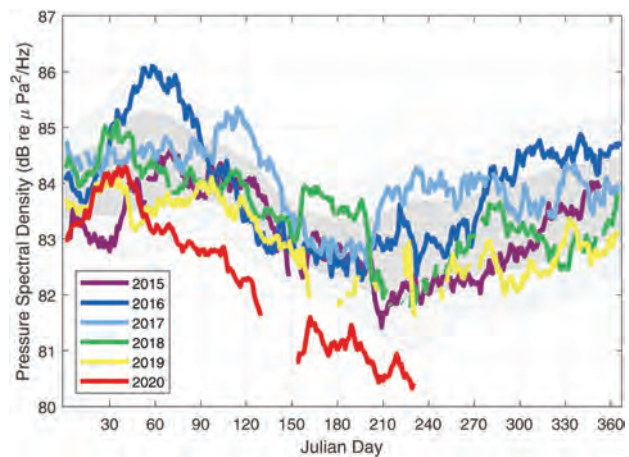


FIG. 4. (Color online) A 45-day moving geometric average of the 63-Hz third-octave band levels for years 2015–2020 (system offline between days 120 and 150 in 2020). Gray shaded areas denote $\pm 1\sigma$ and 2σ about this mean trend based on grouping the data over the first five years and computing the mean and standard deviation over time.

deviation over time, the gray shaded areas denote $\pm 1\sigma$ and 2σ about this mean trend; after about day 60, year 2020 remains less than this mean trend by at least 2σ .

IV. DISCUSSION

The duration over which to compare the influence of suppressed economic activity due to the COVID-19 pandemic on underwater noise levels with prior years is admittedly brief, but the second economic quarter (Q2) of each year provides some corroborating evidence. The Q2 quarterly averages (Table I) of the 63-Hz band levels (Fig. 4) put Q2 of 2020 about 1.6 dB less than the mean of Q2 for the prior five years. Similarly, the 2020 average daily large-vessel count for Q2 (Table I) is reduced by $\sim 19\%$ upon comparing with the mean of Q2 for the prior five years. It is plausible to assume that noise goes as $10 \log_{10}$ of the large-vessel count, with the $\sim 19\%$ reduction yielding a change of about ~ 1 dB, which is nominally consistent. Furthermore, the 2020 Q2 TEU totals for Puget Sound are reduced by $\sim 17\%$. It has been proposed¹⁹ that low-frequency shipping noise levels scale with gross tonnage, and possibly this may be a better predictor.

TABLE I. Metrics for Q2 (April–June).

Year	63-Hz band dB re $1 \mu\text{Pa}^2/\text{Hz}$	Quarterly TEU ^a	Traffic (number of vessels) ^b
2015	83.5	925 735	51
2016	83.3	895 732	52
2017	84.1	929 716	47
2018	83.7	940 241	49
2019	83.1	982 961	47
2020	81.9	775 382	40

^aTwenty-foot equivalent unit (TEU).

^bAverage daily count of vessels length >100 m, passing within the area indicated in Fig. 1.

Note that the estimated reduction of 1.6 dB is less than, for example, the relative reduction in noise levels observed in the rerouting of shipping lanes away from the measurement site, as discussed in the context of the 2008 economic downturn,²⁰ although it does not appear that rerouting is in effect in our study. Nevertheless, our findings over this shorter period of economic change should be viewed as more substantive in quantifying the reduction in noise level and less so in unraveling the precise causative association with measures of shipping activity.

V. SUMMARY

Underwater noise data measured 87 km off Newport, OR between 15 January 2015 and 17 August 2020 are examined by comparing the 2020 data with that from the prior five years. We find a 1.6-dB reduction in the 63-Hz third-octave band spectral level that is typically associated with underwater noise from shipping. The reduction begins on approximately Julian day 60 of 2020 and is relative to the same period in the prior five years, which we infer is the result of reduced shipping and economic activity impacted by the COVID-19 pandemic. Corroboration of this COVID-19 effect is offered through an analysis of AIS shipping data and shipping container activity for Puget Sound. Our results are subtle and must be understood in the context of the significant seasonality within this band on the order of 4 dB, which is in phase with seasonal changes in Northeast Pacific Ocean temperature in the upper 200 m. The seasonally dependent minimum in noise level is concurrent with the reduced shipping activity during the COVID-19 pandemic.

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¹D. S. Kelley, J. R. Delaney and Cabled Array Team, "NSF's Cabled Array: A wired tectonic plate and overlying ocean," in *Proceedings of OCEANS 2016 MTS/IEEE Monterey*, Monterey, CA (September 19–23, 2016), pp. 1–10.

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³D. H. Cato, "Shipping noise impacts on marine life," in *Proceedings of Internoise 2014*, Melbourne, Australia (November 16–19, 2014), pp. 1–6.

⁴R. K. Andrew, B. M. Howe, and J. A. Mercer, "Long-time trends in ship traffic noise for four sites off the North American West Coast," *J. Acoust. Soc. Am.* **129**, 642–651 (2011).

⁵D. P. Percival, "Spectral analysis of univariate and bivariate time series," in *Statistical Methods for Physical Science*, edited by J. L. Stanford and S. B. Vardeman (Academic Press, San Diego, 1994), pp. 313–348.

⁶S. M. Nichols and D. L. Bradley, "Global examination of the wind-dependence of very low frequency underwater ambient noise," *J. Acoust. Soc. Am.* **139**, 1110–1123 (2016).

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Range-Dependent Inversion for Seabed Parameters Using Vector Acoustic Measurements of Underwater Ship Noise

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Abstract—The Intensity Vector Autonomous Recorder (IVAR) measures acoustic particle velocity and pressure simultaneously. IVAR was deployed on the seabed during the 2017 Seabed Characterization Experiment (SBCEX) with the primary objective to study sound propagation within underwater waveguides for which the seabed consists of fine-grained, muddy sediments. In this study, a Bayesian framework is applied to underwater noise recorded by IVAR from a cargo ship traversing the central region of the SBCEX2017 area for the purpose of inversion to characterize sediment properties. The vector acoustic data are in the form of a bounded, nondimensional form known as circularity, a quantity that is independent of the ship noise-source spectrum and that can be interpreted as the normalized curl of active intensity. The inversion model space for the seabed consists of a low-compressional speed layer and underlying basement half-space, with each having compressional and shear components. The interpretative model for producing a replica of the data is based on the plane wave reflection coefficient for a layered, elastic seabed in conjunction with the depth-dependent Green's function that is integrated in the complex wave number plane to obtain pressure and particle velocity fields. The small change in water depth between the location of the ship source and IVAR is addressed using adiabatic mode theory. The inversion results exhibit slow variation over the 20-min observation period, representing approximately 5 km of travel by the ship source.

Index Terms—Acoustic particle velocity, active intensity, circularity, reactive intensity, vector acoustics.

I. INTRODUCTION

THE Seabed Characterization Experiment (SBCEX2017) was conducted in March–April 2017 over an approximate 10×30 km seabed area known as the New England mud patch, located about 95 km south of Cape Cod, MA, USA. The primary objective of SBCEX2017 is centered on the physics of sound propagation in fine-grained, muddy sediments. Study elements

included the inversion of acoustic observations to characterize sediment properties, sediment coring, sub-bottom profiling, and stratigraphic analysis. A large fraction of the experimental area is distinguished by a layer of fine-grained sediment of order 10-m-thick starting at the water–sediment interface and upper sediment sound speed close to the water sound speed at the water–sediment interface. Results from several SBCEX2017 studies are summarized in [1].

In this study, vector acoustic properties of underwater noise from a cargo ship traversing the central region of the SBCEX2017 area are inverted for sediment characteristics using a Bayesian approach. The model space is restricted to describing a low-compressional and low shear-speed layer, and the underlying basement half-space with higher compressional and shear speeds. The observations were made with the Intensity Vector Autonomous Recorder (IVAR), a system that records four coherent channels of acoustic data continuously: one channel for acoustic pressure and three channels associated with a neutrally buoyant tri-axial accelerometer from which acoustic particle velocity is obtained. The system is described by Dahl and Dall'Osto [2] in relation to measurements from broadband SUS (Mk-64) explosive charges made during SBCEX2017.

This study expands upon results reported by Dahl and Dall'Osto [3], with the following key differences:

- 1) range dependence (in water depth) is addressed using an adiabatic approach;
- 2) a different, and arguably more comprehensive, vector acoustic measure, known as circularity, is used in the inversion;
- 3) a greater frequency range is employed in the inversion;
- 4) the inversion parameter set used here accommodates elastic features of the seabed, whereas a nonelastic seabed was modeled in the previous study.

This article is organized as follows. In Section II, the data, measurement period, and location are described, along with the means by which the estimates of circularity are derived from the vector sensor observations. Section III describes our approach to modeling circularity based on the depth-dependent Green's function, a model for the plane wave reflection coefficient for a layered, elastic seabed, and adiabatic constructions of complex fields. The geoacoustic inversion is described in Section IV, and results discussed in Section V. Finally, Section VI concludes this article.

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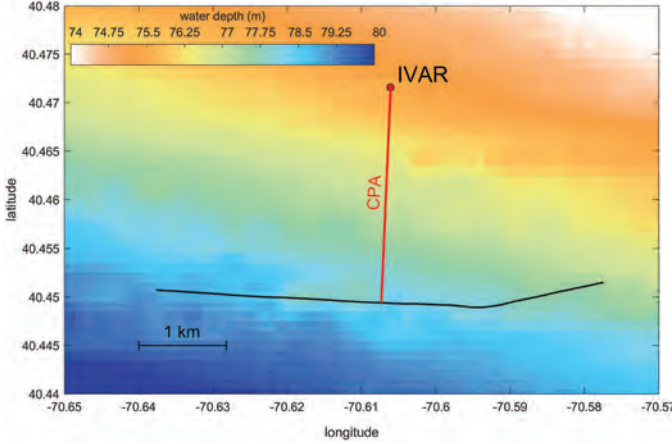


Fig. 1. Transit of *M/V Alice Oldendorf* ± 10 min from the vessel's closet point of approach to IVAR as shown over the approximate bathymetry of the area. The vessel is moving east to west.

II. OBSERVATIONS OF UNDERWATER SHIP NOISE

Underwater noise originating from the transit of *M/V Alice Oldendorf* (IMO number 9183776, length 190 m) was recorded by IVAR on March 8. The vessel's closest point of approach (CPA) occurred at 21:23 UTC. At this time, the water depth at the IVAR location, 40.4716° N, 70.6061° W, was 75.5 m as measured by IVAR, and the vector acoustic measurements were made 1.25 m above the seafloor. Analyses are restricted to data recorded ± 10 min about CPA (see Fig. 1) to exploit the higher signal level as the vessel was transiting approximately east to west at speed 8.2 kn. The CPA range, 2470 m, and speed are based on the ship's Automatic Identification System (AIS).

In the following analysis, the acoustic sample frequency is 5000 Hz, reduced via decimation from the initial sample frequency of 25 000 Hz for convenience, and data are expressed in the frequency domain, formulated by the Fourier transform of the pressure and three acceleration channels using a 1-s data Hanning window. One-sided complex spectra are retained, with each normalized to the variance of the corresponding time-domain data. This operation defines $S_p(f; t)$ as the complex spectrum for pressure and $S_{v_j}(f; t)$ for particle velocity, where f is the frequency and j represents the x, y, z components of velocity (upon division by $-i2\pi f$).

A 10-s moving-time average is taken on the squared spectral quantities, with the center-time value of this average retained establishing ΔT of 5 s for the time index (see also Section IV). For example, the potential energy density spectrum is $(1/2\rho c_w^2)\langle |S_p(f; t)|^2 \rangle$, based on water density ρ of 1027.6 kg/m³ and mean water sound speed c_w of 1470 m/s and with angle brackets denoting the average, and the kinetic energy density spectrum is $\frac{\rho}{2} \sum_{j=1}^3 \langle |S_{v_j}(f; t)|^2 \rangle$. A spectrogram [see Fig. 2(a)] of the potential energy density spectrum corresponding to the transit of *M/V Alice Oldendorf* past the CPA to IVAR, for the 20-min duration studied, shows the increased noise level received post-CPA, presumably owing to greater stern-aspect radiated noise. Time–frequency displays for this measure, the companion

kinetic energy density, and the phase of cross-spectrum corresponding to an hour-long time span of the transit are shown in [3].

This study uses a nondimensional form of the data known as circularity $\Theta(t, f)$, which can be interpreted as the normalized curl of active intensity [4]. As in the case for the phase of the cross-spectrum used in [3], the estimates of circularity as a function of time and frequency are conveniently independent of ship source level. However, the estimates of $\Theta(t, f)$ also embody a greater degree of information concerning seabed properties than the data used in [3] because of, for example, greater sensitivity to multimode interference and more gradual change between extreme values of ± 1 that are better utilized in an inversion scheme.

Estimates of $\Theta(t, f)$ are computed by finding active I_j and reactive Q_j intensity components (averaged in the same manner)

$$I_j(f; t) = 0.5 \langle \text{Re}\{S_p(f; t)S_j^*(f; t)\} \rangle \quad (1)$$

and

$$Q_j(f; t) = 0.5 \langle \text{Im}\{S_p(f; t)S_j^*(f; t)\} \rangle. \quad (2)$$

Next, put

$$|I|^2(f, t) = \sum_{j=1}^3 I_j^2 \quad (3)$$

and

$$|Q|^2(f, t) = \sum_{j=1}^3 Q_j^2. \quad (4)$$

The two horizontal components ($j = 1, 2$) are combined to estimate radial (or r -component) active and reactive intensity magnitude as follows $I_r(f, t) = \sqrt{I_1^2 + I_2^2}$ and $Q_r(f, t) = \sqrt{Q_1^2 + Q_2^2}$, and vertical components I_z, Q_z are associated with $j = 3$.

The estimate of circularity $\Theta(t, f)$ is thus given by [4]

$$\Theta(f; t) = 2 \frac{I_r Q_z - I_z Q_r}{|I|^2 + |Q|^2}. \quad (5)$$

Equation (5) is a bounded indicator of the vector acoustic field (between ± 1), taking on the maximum absolute value in the regions of destructive interference and shown to be effective in tracking the frequency dependence of waveguide interference features, including study of the waveguide invariant β [4]. Here, a scalar form is generated (by using I_r and Q_r) to allow comparison with a normal mode-based model for an underwater waveguide with cylindrical symmetry that supports only radial and vertical components of particle velocity. Thus, there is a small approximation in effect, insofar as I_r and Q_r can only be positive; however, instances where these can be negative occur in certain waveguide interference features that are spatially rare and have an extremely low signal level [5].

The estimate of $\Theta(f; t)$ [see Fig. 2(b)], like the potential energy density, also shows the characteristic interference pattern for the closing and opening about the CPA, but with added detail such as transition between modes. Approximate symmetry about the CPA is evident, with small deviations from symmetry that are

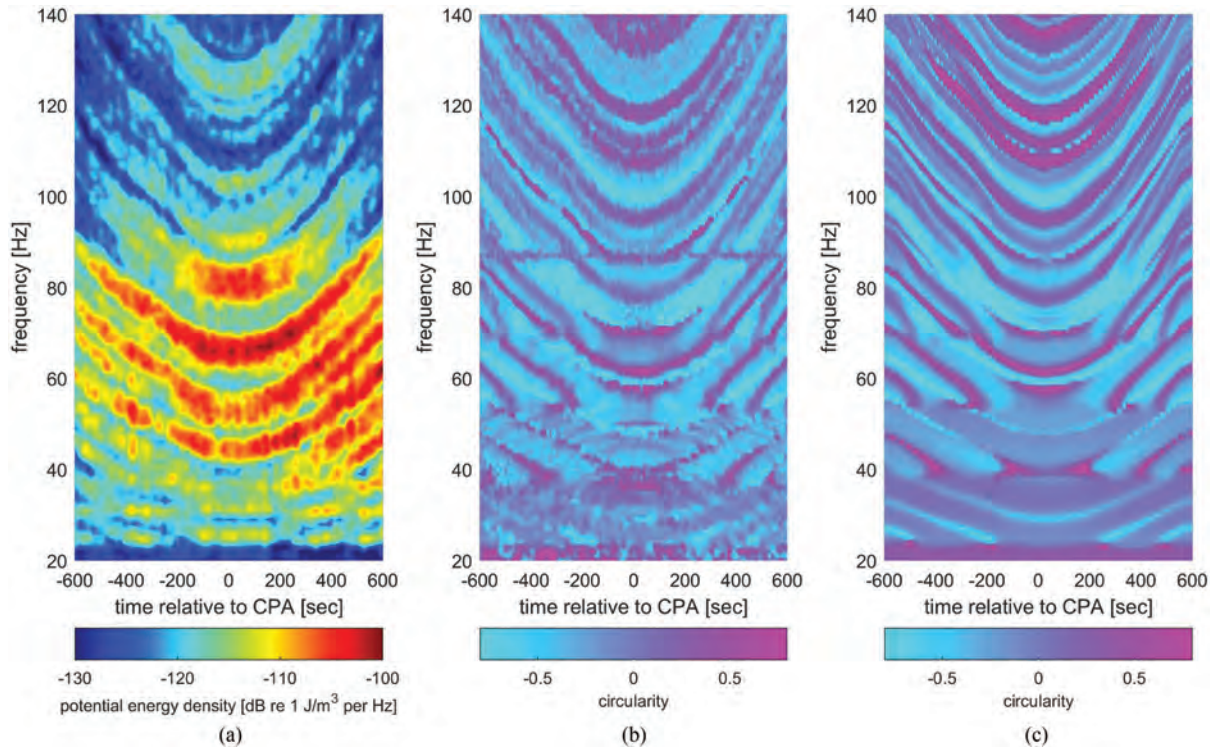


Fig. 2. (a) Potential energy density recorded during the transit of *M/V Alice Oldendorf* past the IVAR sensor. (b) Corresponding estimate of circularity (86–88-Hz band is corrupted by system noise). (c) Model replica of circularity generated from a smoothed version of the inversion results, as discussed in Section V. Although the lowest frequency displayed is 20 Hz, data used in the inversion are limited to the frequency range 23–140 Hz.

postulated to be due to the slowly changing water depth under the vessel and changing bottom properties over the course of the transit.

Data over the frequency range 23–140 Hz, every 1 Hz, are used in the inversion [see Fig. 2(b)] with the exception of the 86–88-Hz band, which is corrupted by internal instrument noise, giving a total of 115 frequencies. The 1-Hz frequency spacing captures changes in the mode structure, with a smaller spacing increasing the dimensionality of the data with little or no advantage in the inversion. The lowest frequency of 23 Hz is on the very edge of reliable detection, owing to the receive bandwidth of IVAR (changed since 2017); we retain this frequency because of the interesting contrast between 23 and 24 Hz.

III. FORWARD MODELING

Following the methods of Dahl and Dall'Osto [3], the forward model used in the Bayesian inversion is based on a sum of normal modes for acoustic pressure and particle velocity. Here, however, we first obtain a model for the plane wave reflection coefficient for a layered, elastic seabed R_b , then use R_b in conjunction with the depth-dependent Green's function [6] that is integrated in the complex wave number plane to obtain pressure and particle velocity fields. Other more numerically based approaches can be used for this purpose, but this approach centered on finding R_b allows for an effective exploration of seabed parameter space that includes elastic properties.

A. Plane Wave Reflection Coefficient for a Layered Elastic Seabed Applicable to the SBCEX2017 Experimental Area

We compute the plane wave reflection coefficient R_b as a function of frequency for a sediment layer of thickness H overlying a half-space, with both layers including shear effects, following the matrix formulation of Vidmar and Foreman [7]. The physical model for the sediment [see Fig. 3(a)] is simplified from that used by Vidmar and Foreman, insofar as they allow sediment parameters within the layer to vary. The simplification to constant parameter values within the layer is because of the limited resolvability of our ship underwater noise data, e.g., it is not realistic to resolve gradients or other variation within layer H . The magnitude of R_b versus the grazing angle for the case of 120 Hz (solid line) is shown in Fig. 3(b), with sediment parameter values (representative of our final inversion results) used to generate R_b shown in Fig. 3(a). For comparison, the dotted line shows the case where shear effects are removed.

The characteristic function for finding modal eigenvalues k_n for water depth D satisfies

$$1 + R_b(k_n)e^{2i\gamma_n D} = 0 \quad (6)$$

where γ_n is the corresponding vertical wave number in the water column. Given the frequency range 23–140 Hz, searching for the roots of (6) is facilitated by using a starting seed value for k_n based on assimilating the acoustically transparent mud layer into the water column, giving a new water depth of $D + H$. The basement shear is temporarily ignored for this purpose (but not

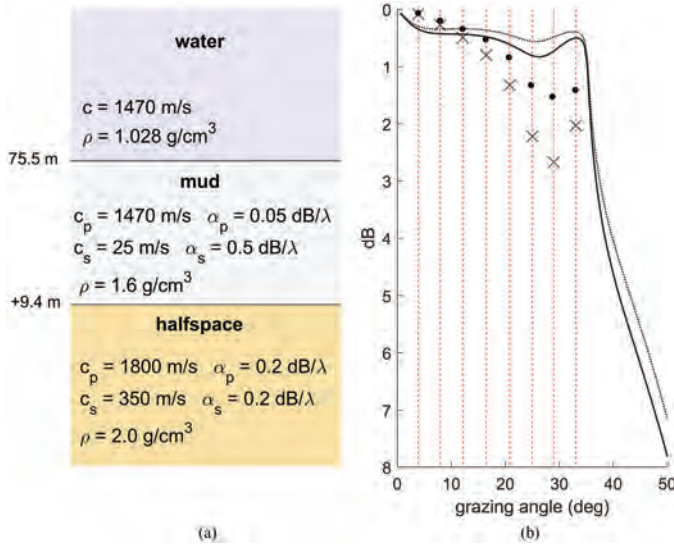


Fig. 3. (a) Physical model of the sediment for computing the plane wave reflection coefficient R_b . (b) Magnitude of R_b (solid line) in terms $-20 \log_{10} |R_b|$, versus the grazing angle for the case of 120 Hz based on the parameters shown in (a). The dotted line shows the case when elastic parameters are set to 0. Dashed vertical lines show the equivalent grazing angles for the eight trapped modes. Loss for given modes (upon interpreting the y-axis in dB/km) are shown by the “X” symbol, with dots representing the case with elastic parameters set to 0.

compressional attenuation) and the method in [8] is used to find an approximate k_n for a seed value, after which further iterations on (6) commence, leading to the final estimate of k_n . This search method is applied to both trapped and leaky modes.

The roots of (6) are complex wave numbers k_n that embody the propagation angle of the modes and the losses incurred with range exceeding cylindrical spreading. Equivalent grazing angles $\cos^{-1} \text{Re}\{k_n\}/k$, where k is the corresponding wave number for a given frequency, for the eight trapped modes at 120 Hz fall on the plateau of the reflection coefficient [the dashed vertical lines in Fig. 3(b)]. The imaginary part of k_n [see Fig. 3(b)] is quantified as a loss in dB/km equal to $20 \log_{10} [\exp(-\text{Im}(k_n)1000)]$, where the x-symbols are for the case with seabed parameters as shown and dots are for the case where shear effects are removed. The loss per km for each mode generally increases with mode number, with greater loss for the elastic case, as expected. However, the presence of the shear layer also produces a rebound in the reflection coefficient at some frequencies. Note that the loss per km for the ninth mode, which is leaky, is about 20 dB/km and not shown on this plot. These effects, as manifested, in any given R_b as a function of frequency are subtle, but nevertheless observable in our measurements of $\Theta(f; t)$, particularly at frequencies encompassing a transition from leaky to trapped modes and in reduced contribution of higher order modes.

The residue associated with a given mode with horizontal wave number k_n is found upon evaluation of $(\partial/\partial p)(1 + R_b e^{2i\gamma_n D})|_{p=k_n}$, where p is a member of the complex horizontal wavenumber plane. Here, the quantity $(\partial/\partial p)R_b|_{p=k_n}$ is necessarily evaluated numerically; note that Ellis and Chapman [9] provide a useful analytic solution to the

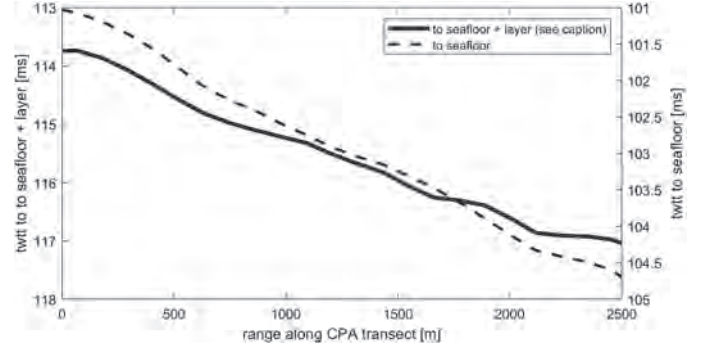


Fig. 4. Two-way travel times along the CPA transect shown in Fig. 1 to seafloor (dashed line) and to transition between the low-speed sediment layer and higher speed sediments (solid line). These data are parsed from structure maps of two-way travel time measurements for the seafloor and seabed interfaces by Goff *et al.* [10]. Range 0 represents the IVAR location; although not essential in current analysis, exact equivalence to 75.5 m requires a slightly higher sound speed in effect during the travel time measurements.

residue evaluation, applicable to an elastic half-space but without the overlying elastic layer of thickness H .

Having established a residue contribution for each mode, for which we generally find approximately ten modes with varying trapped-to-leaky proportion depending on frequency, contour integration in the complex horizontal wave number plane is completed via the sum of these residue contributions. Note that the contribution associated with a Scholte wave or zeroth-order mode [9] is not evaluated because the frequency range is too high to observe such a contribution, and the surface ship excitation of a zeroth-order mode within this frequency range is not significant.

B. Adiabatic Construction of the Pressure and Particle Velocity Fields

The tidal mediated water depth at the IVAR location was 75.5 m during the 20-min observation period. The water depth for the source excitation, as represented by the changing position of *M/V Alice Oldendorf* (see Fig. 1), varied between 77 m (at CPA -10 min) and 79 m (at CPA $+10$ min). This depth was estimated by the AIS location of the vessel, combined with structure maps of two-way travel time measurements¹ for the seafloor and seabed horizons [10]. The change in depth between IVAR along any given transect connecting the two positions is assumed to be linear, as can be inferred in an approximate sense by Fig. 1. This assumption is verified at CPA by the two-way travel time to the seafloor for this transect parsed from the structure maps (see Fig. 4) showing reasonable agreement with a linear slope in the depth between the IVAR and ship positions.

Thus, we apply an adiabatic approximation, putting water depth at ship source location D^s , for example, equal to 78 m at CPA, with water depth at the fixed IVAR receiver location D^r equal to 75.5 m. Given the changing ship position, D^s varies

¹ Structure maps [10] are kindly provided by John Goff. Depth adjusted for tidal influence at the time of CPA.

in the data modeling used in the inversion, depending on the particular transect connecting the location of the vessel to that of the IVAR. The adiabatic approximation further assumes that the mud-layer depth H remains, at least on average, independent of this changing depth. This assumption is similarly supported by the two-way travel time data from the sea surface to the interface between the low-speed sediment layer and higher speed sediments (see Fig. 4, solid line), which follows a similar slope as the two-way travel time to the seafloor.

The complex acoustic pressure field as a function of frequency $P(f)$ for this combination of D^s and D^r is

$$P(f) = i\pi \sum_n N_n^s \sin(\gamma_n^s z^s) N_n^r \sin(\gamma_n^r z^r) H_0^{(1)}(\bar{k}_n R) \quad (7)$$

where $\bar{k}_n$ is the mean wave number in effect between depths D^s and D^r [11], and $H_0^{(1)}$ is the zeroth-order Hankel function of the first kind. The mode-dependent excitation coefficient is split into two parts to account for the difference in water depth at the source and receiver, where

$$N_n^r = \sqrt{4ik_n^r / \frac{\partial}{\partial p} (1 + R_b e^{2i\gamma_n^r D^r})} \Big|_{p=k_n^r} \quad (8)$$

and where k_n^r and corresponding γ_n^r solve the characteristic equation governed by D^r . An analogous computation is made for N_n^s using k_n^s and γ_n^s established by the water depth at source D^s .

The sensor receiver depth z^r equals 74.25 m, or 1.25 m above the seabed on the IVAR platform. The source depth z^s is set to 5 m, because our experience with this setting is that source depths in the range 2–10 m yield the same modeling result as anticipated for a ship near-surface source. To find $\bar{k}_n$ for a given candidate seabed, we precompute k_n based on water depths between 75.5 and 79 m in 0.2-m steps. We do not have the depths between the vessel and IVAR for any given source–receiver propagation path, but the reasonably uniform bathymetric slope between these two points supports taking a simple, linear average between k_n found at a given D^s and that found at $D^r = 75.5$ m. Finally, optimization searches for range R is over a uniform search bound centered on the AIS range (i.e., prior information) for a given transect (see Section IV).

The complex horizontal $V_r(f)$ and vertical $V_z(f)$ particle velocity can now be computed as follows:

$$V_r(f) = \frac{1}{2f\rho_w} \sum_n \bar{k}_n N_n^s \sin(\gamma_n^s z^s) N_n^r \sin(\gamma_n^r z^r) H_1^{(1)}(\bar{k}_n R) \quad (9)$$

where $H_1^{(1)}$ is the first-order Hankel function of the first kind and ρ_w is the water density, and

$$V_z(f) = \frac{-1}{2f\rho_w} \sum_n \gamma_n^r N_n^s \sin(\gamma_n^s z^s) N_n^r \cos(\gamma_n^r z^r) H_0^{(1)}(\bar{k}_n R). \quad (10)$$

The complex pressure and particle velocities, each as a function of frequency for set range R , are assembled into a model for $\Theta(f)$ using

$$I_r(f) = \frac{1}{2} \text{Re}\{P(f)V_r(f)^*\} \quad (11)$$

and

$$I_z(f) = \frac{1}{2} \text{Re}\{P(f)V_z(f)^*\} \quad (12)$$

and a parallel construction using the imaginary part yields $Q_r(f)$ and $Q_z(f)$.

The quantities $I_{r,z}$, $Q_{r,z}$, and magnitudes are combined following (5) to yield a model $\Theta(f)$ computed in 1-Hz increments between 23 and 140 Hz, based on a given geoacoustic parameter vector $\mathbf{m}$ (discussed in Section IV), to establish a model vector $\mathbf{d}(\mathbf{m})$ representing a simulated replica of the data.

IV. GEOACOUSTIC INVERSION

As in our previous study [3], a geoacoustic inversion of the data is based within a Bayesian framework. In short, we seek the probability density function (PDF) $P(\mathbf{m}|\mathbf{d})$, an *a posteriori* probability density representing the PDF for model parameters $\mathbf{m}$ given the measured data vector $\mathbf{d}$ corresponding to estimates of circularity. This function equals the conditional PDF for the data given the model $P(\mathbf{d}|\mathbf{m})$, interpreted as a likelihood for $\mathbf{m}$ given that data $\mathbf{d}$ have been observed, multiplied by an *a priori* PDF for model parameters $P(\mathbf{m})$, assumed here to be a uniform distribution within the selected parameter bounds [12]–[14].

The experimental data vector $\mathbf{d}$ is represented by one time t segment of $\Theta(t; f)$ for frequencies 23–140 Hz every 1 Hz; upon removing the three interference frequency bins 86–88 Hz, length $\mathbf{d}$ equals 115. There are 241 such data vectors representing estimates of $\Theta(f; t)$ [one for each transect, e.g., as shown in Fig. 2(b) with time index ΔT of 5 s established in Section II] corresponding to the 20-min (1205-s) observation period, during which the vessel traveled approximately 5 km. Over the 241 separate inversions, we examine the slow variation in the inverted parameters as the vessel traversed the course (see Fig. 1).

Continuing with the example of the CPA transect [time index 0 of Fig. 2(b), and the red line in Fig. 1], we estimate a water depth of 78 m at the vessel location for this transect; using the adiabatic approach, all model vectors $\mathbf{d}(\mathbf{m})$ for this transect are generated on the basis of a linear change in depth between the 78-m water depth at the source (D^s) and the 75.5-m water depth at the receiver (D^r), where the depth change occurs over the nominal range of 2465 m given by the AIS. The AIS range to IVAR is prior information, and a relatively narrow search bound of ± 200 m about this value is used to invert for the final range. In our previous study [3], a much larger range-span for search bounds was evaluated and yielded excellent agreement between the inverted and AIS range using a nominal range-independent model for the seabed; here, given that finding range is a settled issue, the focus is on this range-dependent inversion for geoacoustic parameters.

The model space $\mathbf{m}$ contains four unknown parameters (see Table I), for which we assume uniform prior bounds and equidistant grid search space in each model dimension. To select search bounds for the first three parameters in Table I, we rely on previous results [3] in which median values of the maximum *a posteriori* (MAP) for estimates of c_{sed} , H_{sed} , and c_{base} over a subset of the observations within ± 10 min of CPA were 1478 m/s, 9.4 m, and 1800 m/s, respectively, and thus, our

TABLE I
UNKNOWN PARAMETERS IN MODEL SPACE $\mathbf{m}$ SHOWING SEARCH BOUNDS AND
INCREMENT (MIDDLE VALUE), AND MEAN OF THE MAP VALUES OVER THE
241 TRANSECTS $\pm$ THE STANDARD DEVIATION

Parameter	Unit	Search Bounds	Mean Value, all Transects
H_{sed}	m	8.0 – 0.4 – 10.8	9.4 ± 0.3
c_{sed}	m/s	1450 – 6 – 1498	1470 ± 8
c_{base}	m/s	1725 – 25 – 1875	1793 ± 14
v_{base}	m/s	25 – 60 – 625	350 ± 98

search bounds are nominally centered about these values. The inversion in the earlier study [3] utilized the absolute value of the relative phase between pressure and vertical particle velocity as the observable.

In this study, utilizing $\Theta(f; t)$ with full ± 1 variation, more nuanced properties are observed in the interference pattern, particularly at our lowest observable frequency range, motivating us to include shear effects in forward modeling and inversion. For example, Potty and Miller [15] evaluated the effect of shear on modal dispersion using broadband data from SBCEX2017, and estimate a shear speed of 410 m/s for what they refer to as the deep sediment layer, which corresponds to the basement half-space in our model [see Fig. 3(a)]. Our estimates of v_{base} , here being allowed to vary smoothly as a function of transect, are shown to be nominally consistent with their estimate (see Section V).

The remainder of the model space consists of preset values because these parameters are unlikely to be further resolved with this set of underwater ship noise data, as confirmed by our experiment. Within the low-speed (mud) layer, sediment density ρ_{sed} is set to 1600 kg/m³, representing the nominal value of the range observed in coring operations from SBCEX2017 [16]. Although our data appear to be insensitive to elastic properties within the low-speed layer, we nevertheless include the following parameters for completeness: a sediment shear speed v_{sed} of 25 m/s, also based on observations from the same site [17] (for which given the expected low sediment compressional speed puts the Poisson's ratio close to, but less than, the 0.5 bound for fluid media), and a sediment shear wave attenuation of 0.5 dB/ λ , as informed by the large set of data published in [18, Fig. 5], for which this nominal value of attenuation maps to the low shear speed. Low-speed layer sediment compressional wave attenuation is $0.68 f_{kHz}^2$ dB/m⁻¹, where f_{kHz} is the modeling frequency in kHz; this is based on an approximation² to viscous grain shearing theory [19], e.g., yielding ~ 0.12 dB/ λ at 120 Hz.

Within the basement half-space, the density ρ_{base} is tied to a given c_{base} value using an empirical fit of [21, Table IVA], translating to 1800–2000 kg/m³ for the search bounds of c_{base} in our Table I. The basement compressional wave attenuation is

set to 0.2 dB/ λ , and the shear wave attenuation is set to 0.25 dB/ λ , which are also informed by Bowles [18].

Key steps in the inversion process then follow from [12]; here, put the model–data mismatch column vector $\mathbf{r} = \mathbf{d} - \mathbf{d}(\mathbf{m})$ and find the data misfit function

$$E(\mathbf{m}) = \frac{N_f}{2} \log_e \mathbf{r}^T \mathbf{r}$$

with $N_f = 115$. There remains the assumption that data errors, as represented by $\mathbf{r}$, are Gaussian and uncorrelated [12], [13], and this assumption is addressed further in Section V.

The MAP values for the four geoacoustic parameters studied, including range, are considered the optimal estimates and are found by minimizing the $E(\mathbf{m})$ over the 5-D parameter space. Establishing $P(\mathbf{m}|\mathbf{d})$ follows, given that $P(\mathbf{m})$ is a uniform distribution in all dimensions, and 1-D marginal PDFs for the four geoacoustic model parameters along with range R are found upon summing the 5-D $P(\mathbf{m}|\mathbf{d})$ function over the appropriate model dimensions. As a measure of uncertainty for each parameter estimate, we compute the interval width containing 95% of the probability based on the corresponding 1-D marginal PDF [12].

V. RESULTS AND DISCUSSION

The inversion is completed for each of the 241 transects, i.e., using the 241 data vectors $\mathbf{d}$ [see Fig. 2(b)], with Table I providing an overall summary of results for the four geoacoustic parameters. Fig. 5 displays MAP values (magenta lines) for these parameters and 95% probability width (dashed, black lines) plotted as a function of longitude over the vessel's course (see Fig. 1), noting that vessel latitude is approximately constant over the 20-min period. The 95% probability width for sediment layer thickness H_{sed} , and sediment and half-space compressional speeds c_{sed} and c_{base} , with a few exceptions, reasonably bound the MAP values. For all parameters, the 95% probability width varies depending on transect, but representative values in the vicinity of the CPA are as follows: H_{sed} , ± 0.5 m; c_{sed} , ± 8.4 m/s; c_{base} , ± 25 m/s; and v_{base} , ± 146 m/s, with the 95% probability width for c_{base} approaching the increments in the grid search used in the inversion (see Table I). Estimates for the shear speed in the half-space v_{base} are, for some transects, encumbered by large uncertainties that press up against the search bounds (dotted, black lines), generally occurring when the MAP estimates are also very low. (When this occurs the MAP estimates [see Fig. 5(d)] are not displayed.)

A smoothed version of the results (see Fig. 5, cyan line) based on a 20-point (100 s) moving average, provides a sense of the slow variation in the average, effective seabed parameters that describe the seabed between the IVAR receiver and the ship source as the latter varies in longitude. The mean and standard deviation of the MAP values (see Table I) provide a single value that is nominally representative of the entire ~ 5 -km transit (see Fig. 1), and the moving average results are bound by this mean $\pm$ one standard deviation. Note that for v_{base} averaging excludes those estimates for which the 95% probability width spans the search bound, and the moving average is extended across data gaps. Taking the means and standard deviations

²Our approximation is of the particular attenuation curve generated by David Knobles, who incorporates sediment parameters for this model that apply to the low-speed, mud-like sediments studied in SBCEX2017.

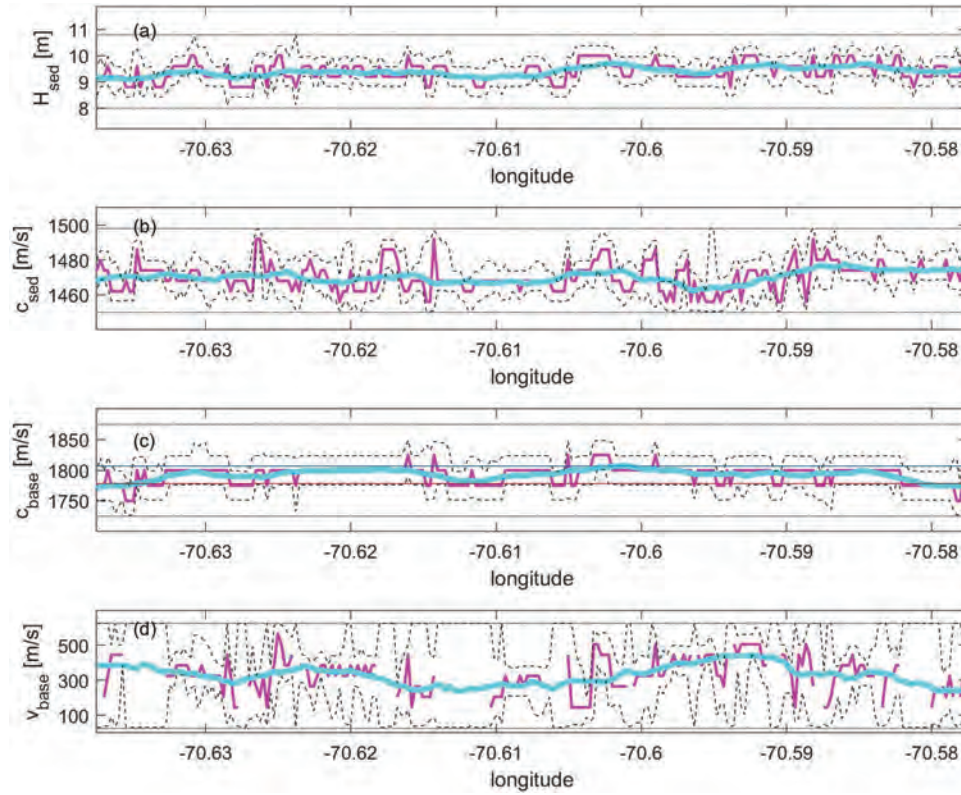


Fig. 5. Inversion results for the four geoacoustic variables given in Table I, plotted as a function of the longitude corresponding to the track of *M/V Alice Oldendorf* (see Fig. 1). (a) Low-speed sediment layer thickness H_{sed} . (b) Sediment compressional speed c_{sed} . (c) Half-space compressional speed c_{base} . (d) Half-space shear speed v_{base} . MAP values (magenta line) and 95% probability width (black, dotted line) are plotted along with a 20-point (or approximately 100 s) moving average (thick cyan line). Black dotted, horizontal lines depict the search bounds for each parameter. MAP estimates of shear speed v_{base} for which the probability width matches the search bound are excluded.

for c_{base} and v_{base} from Table I yields a Poisson's ratio for the sediment in the half-space over the transit of 0.48 ± 0.01 , a value that is consistent with elastic properties of consolidated marine sandy sediments removed from the water–sediment interface [20].

The moving average results (see Fig. 5) are further used to construct a simulated replica of $\Theta(f; t)$ corresponding to the transit of the vessel within ± 10 min of CPA [see Fig. 2(c)]. That is, for each transect, the complex pressure and particle velocity field is computed as a function of frequency using the moving average of the inverted range for that transect (which agrees closely with the AIS range), plus the corresponding set of geoacoustic parameters emerging from the average, and the vessel source depth belonging to the transect. Using the moving average in this operation yields a more realistic simulation of $\Theta(f; t)$; i.e., the MAP values emerging from the inversion over each transect will differ slightly in a necessarily discrete manner.

Three examples of simulated $\Theta(f)$ generated by the specific MAP estimates for geoacoustic parameters and vessel range, corresponding to the inversion on data ± 500 s about the CPA and at CPA (see Fig. 6), compare well with the observations. As in the case of the complete simulated replica $\Theta(f; t)$ [see Fig. 2(c)], prior AIS information is used for the water depth at a given vessel location. For example, the water depth at the vessel

location increases approximately 1 m between the two ± 500 -s transects, where water depth at the CPA transect is ~ 78 m.

The assumption concerning uncorrelated, Gaussian distributed residual errors is addressed with each transect, such as the three shown here. First, we find that the sample autocorrelation function of residual errors shows no effective correlation beyond 0-lag. A chi-square goodness-of-fit test is performed to evaluate the assumption that the residual errors are from a normal distribution, with significance level $p > 0.1$ for the examples shown in Fig. 6. However, for about 10% of the transects, p can fall below 0.05; for these few cases, the distribution of residual errors remains symmetric but tends to show heavier concentration near the mean (leptokurtic).

Our interpretation of some of the detailed, shallow water propagation effects manifested in these data is ongoing, though it is evident that the simulation reproduces observed circularity [see Fig. 2(c)] reasonably well. Going forward, a particularly interesting interpretive challenge is the circularity signal in the model result at 24 Hz [see Fig. 2(c)] at approximately ± 500 s and ± 200 s from CPA, relative to that at 23 Hz, for which there is a change in sign. The circularity data [see Fig. 2(b)] also show the same pattern at 24 Hz, but unfortunately the roll-off in ship noise radiation with decreasing frequency is fast here, with roll-off also apparent in the potential energy [see Fig. 2(a)]. However, we do know that the 23-to-24-Hz transition represents the onset of the

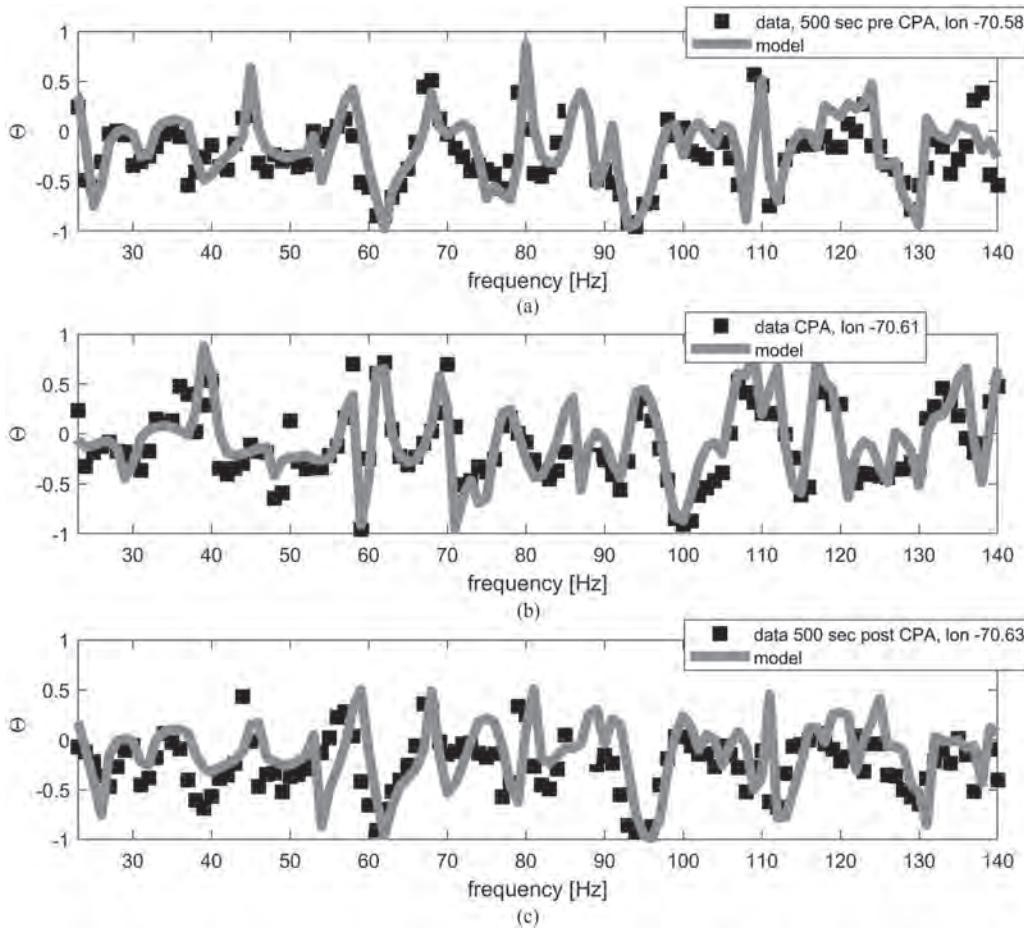


Fig. 6. (a) Estimate of circularity as a function of frequency $\Theta(f)$ for 23–140 Hz, generated by the specific MAP estimates for geoacoustic parameters and vessel range, corresponding to the inversion on data representing 500 s prior to CPA, at which time vessel longitude is -70.58 . (b) $\Theta(f)$ generated by the MAP estimates at CPA, vessel longitude at -70.61 . (c) $\Theta(f)$ generated by the MAP estimates 500 s post-CPA, vessel longitude at -70.63 .

second mode, and this is expected to have a significant effect on circularity [2].

Also, it is possible to observe in the data [see Fig. 2(b)], although very faintly, a pattern in the circularity that is roughly confined to the region between 40 and 55 Hz and which emanates outward from CPA (time 0). This suggests the presence of a weak sound-speed gradient in the seabed, perhaps of order 1 s^{-1} , and the subsequent negative waveguide invariant, which is not captured in our current inversion scheme. Given the general weakness of this feature, our interpretation going forward will rely more on additional forward modeling rather than inversion.

The smoothed, inversion results suggest a kind of variation with longitude; for example, at the start of the observations, the sediment layer depth H_{sed} appears to be about 9.5 m, and this layer depth gradually thins to about 9.1 m near the end of the observations (viewed in an averaged sense). Although the influence of such variation on sound propagation as manifested in our data is subtle, evidence that this is a real effect comes from reconsidering the two-way travel time data first discussed in the context of Fig. 4. For each transect connecting the ship location to the IVAR location, an average sediment thickness is derived by taking the two-way travel time averaged over transect length,

corrected for the first arrival to the seafloor. For example, for the CPA data in Fig. 4, this value is 12.264 ms, which yields a sediment thickness between 9.23 and 9.33 m, upon using the upper and lower bounds of the estimate for c_{sed} (see Table I). Applying this to all transects (see Fig. 7), the results are in reasonable agreement with the moving average inverted results H_{sed} , especially in a linear trend. Importantly, the adiabatic component of our analysis designed to accommodate the slowly changing water depth is essential to capture this trend. Finally, Goff *et al.* [10] and Belcourt *et al.* [22] refer to a transition layer of $O(1)$ m between lower speed, mud-like sediment and the higher speed sandy sediment, the latter considered a half-space in our model, so some degree of ambiguity in delineating this boundary is expected.

The reasonably tight bounds about the parameter estimates for H_{sed} , c_{sed} , and c_{base} (see Fig. 5) point to the degree of sensitivity of the data to these properties. In contrast, the primary influence of parameter half-space shear speed v_{base} is on modal attenuation, as illustrated in Fig. 3(b), and it is reasonable to assume that the ability to measure this parameter is influenced by basic signal fluctuations, as evidenced in the potential energy spectrum [see Fig. 2(a)]. Nevertheless, although our overall average value of

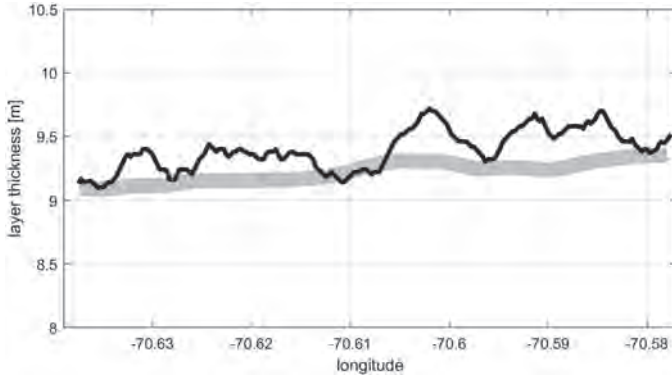


Fig. 7. Estimated thickness of the low-speed (mud) layer (black line) based on the smoothed results for H_{sed} [see Fig. 5(a)]. The gray line is derived from the two-way travel time averaged over each transect connecting the ship location to the IVAR location, based on the data from [10], where the thickness of the gray line maps to the upper and lower bounds of the estimate for c_{sed} (see Table I). Results are plotted as a function of changing longitude for the vessel track (see Fig. 1).

v_{base} is somewhat lower than the estimate of 410 m/s by Potty and Miller [15], we report several individual MAP estimates of v_{base} [see Fig. 5(d)] that are entirely consistent with their estimate. As for remaining geoaoustic parameterizations necessary to describe the low-speed, mud layer, i.e., sediment shear speed, and sediment shear wave and compressional wave attenuation, we reiterate that realistic fixed (or frequency-dependent) prior values are inserted into our model for completeness. Otherwise, these parameters are poorly resolved with our data.

VI. CONCLUSION

This article applies a Bayesian framework for the geoaoustic inversion of vector acoustic properties of the underwater noise from a cargo ship traversing the central region of the SBCEX2017, as measured using the IVAR platform deployed on the seabed at depth 75.5 m. The data are formulated into a measure known as circularity, a bounded, nondimensional quantity that is independent of the ship noise-source spectrum. Observations are made over a 20-min period during which the vessel traveled approximately 5 km east to west, with CPA about 2.5 km south of the IVAR position. The interpretative model used in the inversion process is based on the plane wave reflection coefficient for a layered, elastic seabed in conjunction with the depth-dependent Green's function, and small changes in water depth at the location of the ship source are addressed using adiabatic mode theory. The inversion results exhibit a slow variation (see Fig. 5) over the vessel's observed course, with mean results (see Table I). Given the basic areal geometry of inversion (see Fig. 1), these mean results notionally apply to an approximate seabed area of 7 km².

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Physical effects of sound exposure from underwater explosions on Pacific sardines (*Sardinops sagax*)

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Physical effects of sound exposure from underwater explosions on Pacific sardines (*Sardinops sagax*)^{a)}

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ABSTRACT:

Explosions from activities such as construction, demolition, and military activities are increasingly encountered in the underwater soundscape. However, there are few scientifically rigorous data on the effects of underwater explosions on aquatic animals, including fishes. Thus, there is a need for data on potential effects on fishes collected simultaneously with data on the received signal characteristics that result in those effects. To better understand potential physical effects on fishes, Pacific sardines (*Sardinops sagax*) were placed in cages at mid-depth at distances of 18 to 246 m from a single mid-depth detonation of C4 explosive (4.66 kg net explosive weight). The experimental site was located in the coastal ocean with a consistent depth of approximately 19.5 m. Following exposure, potential correlations between blast acoustics and observed physical effects were examined. Acoustic metrics were calculated as a function of range, including peak pressure, sound exposure level, and integrated pressure over time. Primary effects related to exposure were damage to the swim bladder and kidney. Interestingly, the relative frequency of these two injuries displayed a non-monotonic dependence with range from the explosion in relatively shallow water. A plausible explanation connecting swim bladder expansion with negative pressure as influenced by bottom reflection is proposed. <https://doi.org/10.1121/10.0001064>

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I. INTRODUCTION

There is growing concern about the potential effects of anthropogenic sound on aquatic life (e.g., see papers in Popper and Hawkins, 2016). While there have been studies assessing these potential effects on marine mammals (reviewed in NMFS, 2018; Southall *et al.*, 2019), there have been fewer studies on fishes (reviewed in Carroll *et al.*, 2017; Popper and Hawkins, 2019; Popper *et al.*, 2019; Putland *et al.*, 2019). Moreover, fish studies have focused on effects of sounds produced by vessels, sonars, pile driving (e.g., used in wind farm construction), and seismic air guns (Hawkins and Popper, 2018; Popper and Hawkins, 2019; Popper *et al.*, 2019). In contrast, there have been few studies directed at potential effects of the sounds from underwater explosions used in construction, demolition, military activities, etc. At the same time, the need for more detailed analyses required for protected species drives the interest in having additional data on the effects of high-energy sound that can result from such explosive activities.

The few studies on effects of explosions on fishes are limited in the information they provide because they were,

for the most part, done in restricted acoustic environments (i.e., not open water), often with few controls, and/or with limited procedures for post-exposure necropsy (Coker and Hollis, 1950; Hubbs and Rechnitzer, 1952; Gaspin, 1975; Linton *et al.*, 1985; Yelverton *et al.*, 1991; Goertner *et al.*, 1994). More comprehensive studies were done by Govoni *et al.* (2003) and Govoni *et al.* (2008) on juvenile and larval fishes (length ~ 20 mm). With these size limitations in mind, Govoni and colleagues found that integrated pressure over time interval corresponding to 95% of the energy, or pressure impulse (dimension Pa s), to be the most relevant metric for describing dose-response.

In contrast to earlier work, the study reported here examines the effects of exposure to an explosion on caged adult fish located at different distances from the source using ample controls and detailed necropsy procedures. Of fundamental importance is that this study was done in an open-water location, which is more representative of marine fish habitat. Open water is defined here as a body of water for which the range (length) and width scales are effectively infinite, and in which boundary reflections originate primarily from the seabed and the sea surface.

The initial hypothesis for this study was that effects would decrease with increased distance from the source (i.e., as the acoustic dose in terms of pressure or energy level decreased), as suggested in recent pile driving studies (e.g.,

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Casper *et al.*, 2012; Halvorsen *et al.*, 2012a; Halvorsen *et al.*, 2012b). However, while this pattern was observed for fish located close to the explosion, this was not the case at greater distances. At such distances, effects associated with the underwater waveguide, such as reflection from the seabed, are postulated to play a role in observations of increased rates of injury at some locations farther from the source at this site.

II. METHODS

A. Study overview

The general approach in the study was to transport animals out to the open-water test site, place them in instrumented test cages located at different distances from the source, lower them to mid-water depth, and expose them to a single explosion. Following exposure, the cages were brought to the surface, where the fish were removed from the cages, sacrificed with an overdose of anesthetic, chilled, and then transported to a shore-based laboratory where they were necropsied on the same day. Control fish were exposed to identical conditions as the experimental animals other than the explosion. Data from the sensors on the cages enabled a complete analysis of the acoustic environment to which the fish were exposed. This procedure was repeated on four trial days in October 2018, with a single explosion each day.

B. Experimental species

The study used the Pacific sardine (*Sardinops sagax*), a pelagic species with a physostomous swim bladder commonly found in the waters off San Diego, CA, at depths that include those used in this study (Miller and Lee, 1972). Physostomous swim bladders have a direct connection to the gut (via the pneumatic duct) allowing for easy transfer of gasses in and out of the swim bladder via “gulping” or “burping” of air.

The fish used in the study were obtained from a commercial bait dock in San Diego Bay and held for seven months at the National Marine Fisheries Service’s Southwest Fisheries Center in La Jolla, CA. Fish were then removed from their holding tanks and transported to Naval Base Point Loma (San Diego), where they were kept in 1.2 m deep seawater pens at the mouth of the San Diego Bay for a minimum of two weeks prior to being used in the study. Fish were fed pellet food and cared for daily. At the time of the study, fish had a mean standard length of 166 mm [standard deviation (SD) 9 mm] and mean weight of 62 g (SD 11 g).

All procedures were approved by the Naval Information Warfare Center Pacific Institutional Animal Care and Use Committee (IACUC, protocol 131–2018), and the Navy Bureau of Medicine and Surgery. The study followed all relevant U.S. Department of Defense guidelines for the care and use of laboratory animals.

C. Explosive source

The explosive source for each trial consisted of 3.4 kg of C4 explosive, which corresponds to 4.66 kg of

trinitrotoluene (TNT) using a TNT-equivalent coefficient of 1.37. Detonations occurred at a depth of 10.5 m (± 0.5 m), approximately mid-column at the site, to avoid immediate interaction of the explosion with the bottom. The detonations were conducted by Navy explosive ordnance demolition personnel in accordance with the U.S. Navy’s Hawaii-SOCAL Environmental Impact Statement¹ and associated permits.

D. Experimental site

All trials occurred within the U.S. Navy’s Silver Strand Training Complex, an area approximately 5 km offshore from San Diego. All instrumented experimental cages and other acoustic sensors were located along a line parallel to the shoreline over which the average water depth was 19.5 m, with little bathymetric variation over the transect (about 250 m long). The seabed within the immediate area is largely composed of unconsolidated, sandy sediments.

E. Fish cages, basic measurement geometry and acoustic instrumentation

The approximately 0.35 m³ cylindrical cages were covered with 1.5 cm knotless polyester mesh netting and suspended within a frame made from polyvinyl chloride (PVC) tubing (Fig. 1). The cages were suspended close to mid-water using a 9.2 m line with an approximately 20 kg weight to anchor the station to the seabed, which put the cage center at a depth of 10.5 m (± 0.5 m). A closed cell foam float was tied at the top of the cage to ensure that it maintained correct orientation. From this subsurface float, another line was run to the surface and attached to either marker buoys (control cages) or inflatable rafts with the acoustic monitoring system

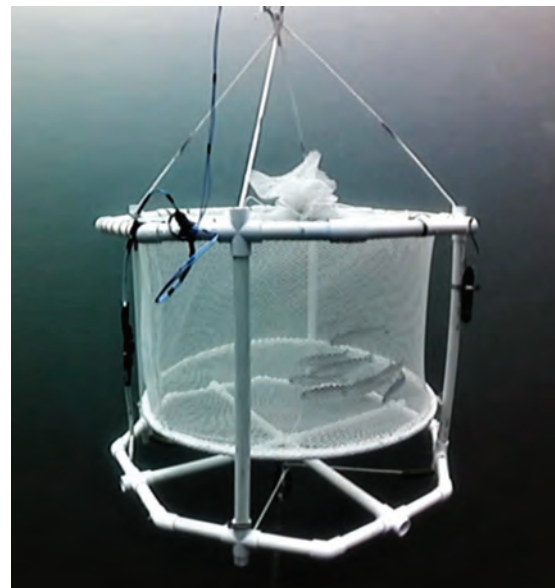


FIG. 1. (Color online) Underwater photo of one of the cages taken with a ROV prior to exposure to the explosion. Details of the cage, instrumentation, and its suspension are discussed in the text. A depth sensor is shown on the right of the cage and a pair of blast probes on the left. Pacific sardines can be seen schooling in the cage.

(discussed in detail in the next paragraph). All cages beyond 50 m from the blast were equipped with depth sensors. Depth sensors could not be placed closer than about 50 m without being damaged; however, depth-consistency over the four instrumented cages gives confidence in assigning the depth for such case.

The four closest experimental cages were each instrumented with two, non-directional, tourmaline blast sensors (PCB W138A01, PCB Piezotronics, Depew, NY) with nominal sensitivity of 0.73 mV/kPa, equivalent to a received sensitivity of -243 dB re V/ μ Pa. The two sensors (for redundancy) were wired to custom-designed recording and transmitting units housed in small inflatable rafts situated above each cage (see Fig. 2), which recorded the acoustic data at a 2-MHz sampling rate. Data from all four rafts were time-synchronized with a Global Positioning System (GPS) and recording was started remotely by a computer base station located on one of the monitoring boats.

The acoustic field at the farthest (or 5th) cage was measured by placing a nine-element vertical line array (VLA) as close as possible to the cage (Fig. 2). Acoustic data from the nine VLA elements (ITC 1042 non-directional hydrophone, nominal sensitivity of -206 dB re V/ μ Pa, Gavial ITC, Santa Barbara, CA) were coherently recorded at a 0.5-MHz sampling rate. The VLA elements were separated by 2 m, and data from the VLA hydrophone at depth most closely matching the cage depth was taken as a measure of the acoustic field at this far range.

F. Explosion exposure paradigm

Experimental procedures were refined and preliminary fish cage ranges from the explosion were established during a pilot trial in September 2018 (data from that trial are not used in the results reported here). This established a protocol that was then followed during each of the four experimental trials.

On the morning of each of the four trials, approximately 80–90 fish were transferred by dip-net to three cylindrical holding tanks (height 1.5 m, diameter 0.7 m) located on the

R/V *Ecos*, a 12.2-m-long Navy research vessel. Transport to the offshore research site took approximately 45 min, during which time the holding tanks were continuously aerated. In addition, fresh seawater was introduced to the holding tanks each time the vessel stationed to deploy fish cages or instrumentation. Dissolved oxygen levels were monitored at regular intervals and airflow was increased when levels dropped below 100%.

Upon arrival at each designated cage location, a cage (Fig. 1) was lowered halfway into the water. In most cases, ten fish were dip-netted into the cage. The cage was closed and slowly lowered (over a period of about 2 min) to the experimental depth. In a few instances, a cage received 9 or 11 fish, and this numerical variation was incorporated into subsequent statistical analysis. Fish displaying abnormal swimming in the transport containers were not used for the study.

The first two cages (controls) were deployed on the test range at the same depth as exposure cages. Once the control cages were positioned, the vessel stationed the five test cages along a 250-m-long transect (Fig. 2) originating from the detonation point. Over the four days of trials, 20 test cages were placed at distances ranging from 18 to 246 m. Once the test cages were in position, the vessel returned to the control cages, lifted them to the surface, and retrieved the fish. Control fish were treated identically to experimental fish other than for exposure to the explosions and were in the water for approximately the same duration (about 3 h) as the experimental fish.

After each test and control cage was positioned at depth, it was inspected with a remotely operated vehicle (ROV) operated from a small boat to ensure that the cage had deployed properly and that the fish were actively swimming (Fig. 1). Another small boat used GPS to get an accurate estimate of test cage position by stationing directly over the cage, and thus could determine distance from the explosion. This determination was critical because it was not possible in the open-water conditions to position a cage in a precise, pre-established location using the deployment procedure.

Concurrently with the deployment of cages, a U.S. Navy Explosive Ordnance Disposal (EOD) dive team

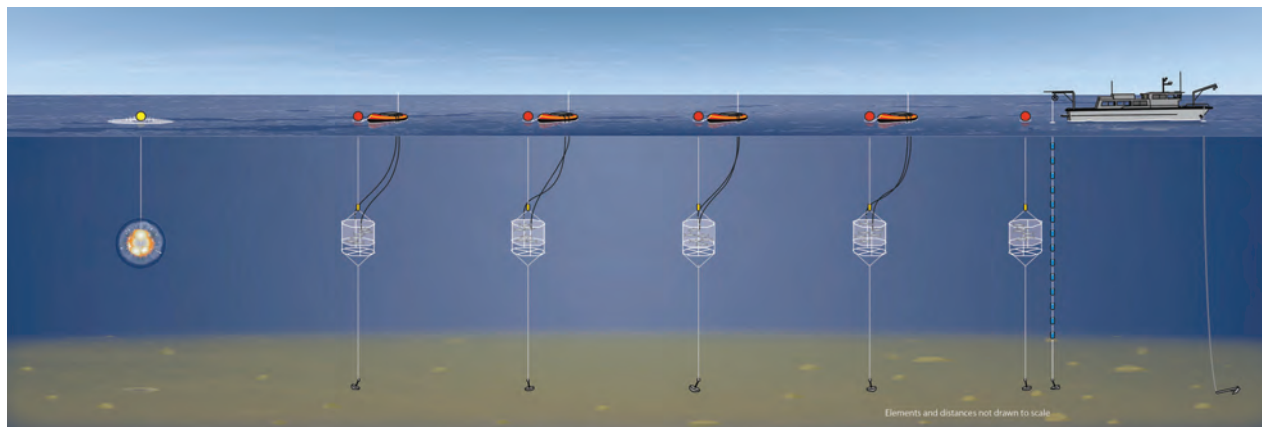


FIG. 2. (Color online) Basic geometry (not to scale) for each explosive trial (see text for additional information). The explosion is to the left. Five cages are deployed midwater out to maximum range of approximately 250 m from the source. Note the tourmaline blast sensors on the four cages closest to the source. These are attached by cable to the raft at the surface (red). The VLA was stationed adjacent to the farthest cage.

prepared the explosive charge. Once all fish cages were properly placed, the EOD dive team set the explosives at the predetermined location (with known GPS coordinates) and depth (10.5 m). Upon confirmation that all systems were recording and that a required mitigation zone around the blast site was clear of marine mammals, the EOD team began a countdown and the charge was detonated.

Approximately 15 min post-detonation (depending upon clearance from the EOD dive team), the R/V *Ecos* began recovery of the test cages. These were recovered in the same order they were deployed in order to maintain the same approximate time in the water (2 h 50 min $\pm$ 20 min).

Immediately upon recovery of a cage, all live fish were euthanized by placing them in a solution of buffered anesthetic (MS-222, tricaine methanesulfonate) for approximately ten minutes beyond the last observed opercular movement (i.e., respiration). The fish were then removed from the anesthetic solution and immediately placed in plastic bags labeled to indicate the treatment (i.e., distance to the explosion or control). The few (eight) fish that were dead when brought to the surface in the cages were treated similarly except that they were not placed in the anesthetic and they were stored in separate bags from the euthanized fish. All bags were wrapped in bubble wrap or towels to prevent localized freezing of tissues when they were placed on ice packs. In addition, any animals that were transported to the test site but not deployed in exposure or control cages were euthanized after cages were deployed and subjected to the same storage procedures as used for the other fish. These fish were examined to inform any potential effects that resulted from handling or husbandry methods during initial dip netting and transportation to the test site (e.g., external abrasions).

G. Fish preparation and necropsy

Once the boat returned to shore, the chilled euthanized animals were immediately moved to the laboratory. Using a

pre-determined randomization sequence, fish were taken from different bags (representing different treatments) for necropsy. Each fish received a unique identification number and was weighed, measured, and given to one of the individuals performing necropsies who were blind to the treatment of the fish.

Necropsy procedures were adapted from past studies examining the effects of impulsive anthropogenic sound on fishes (e.g., Casper *et al.*, 2012; Halvorsen *et al.*, 2012a; Halvorsen *et al.*, 2012b; Popper *et al.*, 2016). Dissection procedures were standardized among individuals performing necropsies and identification of natural variations in organs and tissue (e.g., color, size, and placement) was established by observing the baseline anatomy of Pacific sardines.

When given a fish, the investigator performing the necropsy first examined the exterior of the animal and noted any damage. They then opened the fish by making a ventral mid-line incision starting at the vent (cloaca) and moving forward to the pectoral girdle. Both sides of the cut were carefully pinned apart to reveal the internal organs. Using a blunt probe, the organs and tissues were inspected for any evidence of injury (see Table I for organs and tissues examined).

Each investigator made note of injuries or other observations (including any on tissue not on the observation list) using a tracking sheet. Photographs were taken of suspected injuries. Examination of each fish took 10–20 min, depending on the extent of damage. Once necropsy was completed, the tracking sheet was given to a data handler who entered the findings into a database. A second person later reviewed each entry for accuracy.

III. RESULTS

All but 8 of the 209 experimental fish were retrieved alive after exposure to the explosion. Four of the mortalities were at the closest cage (18 m). Note that since live fish were euthanized shortly after they were brought to the surface, it is not possible to know whether they would have

TABLE I. Summary of effects data. Data in columns 2, 3, and 4 rounded to one decimal. See text for explanations of each column. Bold injuries show statistical significance.

1 Injury	2 Pooled control rate (%)	3 Pooled injury rate (%)	4 SD (+/–)	5 <i>p</i> -value homogeneity with range	6 <i>p</i> -value injury significance
Spleen hematoma	0	0	-	-	No injury
Spleen hemorrhage	0.0	0.0	-	-	No injury
Body muscle hematoma	0.0	1.9	0.9	0.667	0.384
Pyloric caeca hemorrhage	1.4	3.0	2.0	0.073	0.389
Hepatic hemorrhage	0.0	2.9	1.2	0.424	0.197
Gall bladder damage	0.0	0.5	0.5	0.624	0.484
Swim bladder hematoma	0.0	3.3	1.0	0.175	0.144
Burst capillaries	0.0	3.3	1.2	0.030	^a
Fat hematoma	1.0	48.8	3.5	0.394	<0.001
Reproductive blood vessel rupture	0.0	15.8	2.5	0.017	<0.001 ^b
Swim bladder rupture	0.0	19.6	2.7	0.001	<0.001
Kidney rupture	0.0	25.4	3.0	0.010	<0.001

^aInjury rate shows statistical significance ($p < 0.01$) only when comparing the fish nearest the source to the controls [see Fig. 4(a)].

^bObservation of this injury may not be possible in instances of severely ruptured swim bladder.

succumbed to internal injuries at any time following exposure. No mortalities were observed in control fish.

The ROV videos recorded prior to the detonation showed that most fish were schooling (i.e., swimming closely together in the same circular direction, see Fig. 1) and none were dead. Only about 4% were not schooling or were swimming into the top or sides of the cage netting.

A. Physical effects

1. External effects

Each fish was examined externally to determine if exposure to the explosions produced physical damage including bleeding and abrasions to the eyes, gills, inside of mouth, fins, and external body wall. No differences in type or number of injuries were seen between experimental animals and control animals (0.2 being the minimum p -value for the hypothesis of no observed difference for the 13 itemized external injuries.) Thus, it is inferred that the external injuries were the result of handling or could have occurred while the fish were being held in the seawater pens prior to use.

2. Internal effects

Initially, injury assessments were based on the list of 18 possible internal injuries identified in the

mentioned studies. However, not all of the 18 possible internal injuries were found in the current study (e.g., intestinal hematoma and hemorrhage) and were therefore eliminated from consideration in the analysis. In addition, a previously unreported injury, reproductive blood vessel rupture, was noted during the current study and added to those analyzed. Therefore, a total of 12 internal injuries were found in the current study in one or more animals (see Table I).

The cumulative results from the set of 12 internal anatomical observations are shown in Table I. Images of several types of injuries are shown in Fig. 3. In Table I, column 2, the pooled control rate, identifies the percent injury for a given effect within the set of 73 control fish used over the four trials. Pooling of these data over the four trials is warranted based on a chi-square (χ^2) test of homogeneity ($p = 0.78$).

Column 3 of Table I, pooled injury, identifies the percent injury based on the pooling of the 20 unique cage ranges sampled over the four trials. Column 4 provides the injury rate SD that incorporates treatment sample size (209), control sample size (73), and any non-zero control injury rates, based on Ricker (1975, p. 123). The p -values for a χ^2 test of homogeneity over the range for given injury are identified in column 5. The p -values for ruptured swim bladder, kidney rupture, burst capillaries, and ruptured reproductive

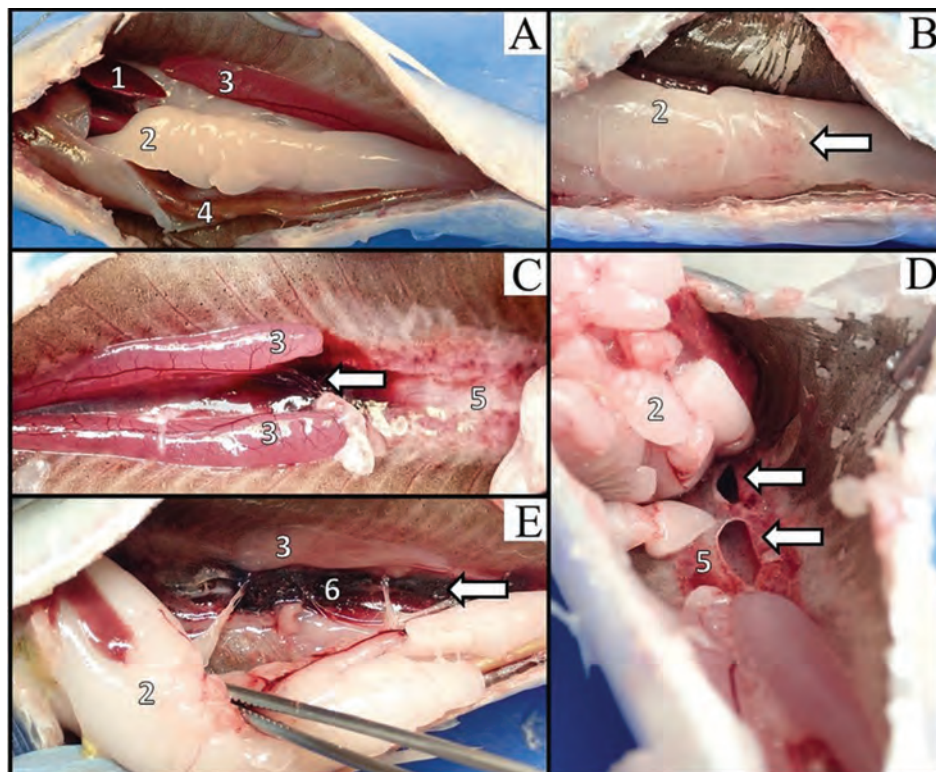


FIG. 3. (Color online) Photographs of internal dissections of Pacific sardines. Numbers indicate the following organs/tissue: (1) liver, (2) fat, (3) gonads, (4) intestine, (5) swim bladder, and (6) kidney. White arrows indicate internal injuries that are statistically different between control and experimental animals. Views are from the ventral side of each animal. (A) Fat from a control fish visible upon opening the body cavity, ventral to the gut; (B) fat hematoma (animal 121 m from explosion); (C) reproductive blood vessel rupture (animal 182 m from explosion); (D) swim bladder rupture (animal 121 m from explosion); (E) kidney rupture visible after removal of swim bladder (animal 30 m from explosion). All fish were of similar size.

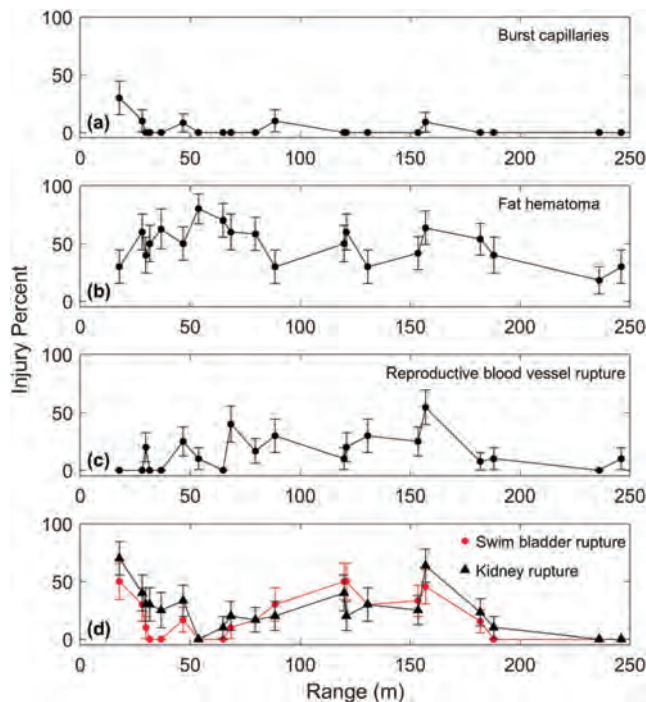


FIG. 4. (Color online) Percent injury for each cage according to their distance from the explosion over the four trials. Data are only shown for injuries that are statistically different from controls (Table I). Error bars represent $\pm$ one SD based on specific pooled control rate (Table I) and number of fish in given cage using Ricker (1975). See text for further explanation.

blood vessel are less than 0.05, indicating a rejection of hypothesis that injury is independent of range.

Finally, column 6 provides a single measure of overall injury significance, in the form of the p -value for χ^2 test of H_0 : non-injury rate is independent of exposure (or non-injury rate of controls not statistically different from exposed fish). As a reminder, the exposed injury rate used in this analysis is based on the pooling of all 209 exposed fish over the 20 cage ranges, such pooling will tend to increase the p -value for this test. Thus any p -value less than 0.05 is a strong indicator that the injury rate is significant. Similarly, p -values greater than 0.05, while in combination with that injury being statistically homogeneous in range, is an indicator that the injury is not significant. Some exceptions to this classification are identified in Table I.

Results show five injuries that were statistically significant plotted as a function of range in Fig. 4. Burst capillaries are included in this set despite this injury having a relatively low pooled injury rate (column 3, Table I). However, in this case, pooling is not supported ($p = 0.03$, column 5, Table I), and the p -value for injury significance falls below 0.01 upon assessment of the data observed within 50 m of the source [see Fig. 4(a)].

In contrast, fat hematoma [Fig. 4(b)] and reproductive blood vessel ruptures [Fig. 4(c)] were found in many fish at various distances. Indeed, fat hematoma was found in all experimental animals at all distances, but the degree of hematoma, and the variety of location in fat located in different regions of the internal body cavity, makes it hard to

correlate with swim bladder motion or any other physical or physiological effect. Findings for reproductive blood vessel ruptures may be related to the impact of swim bladder motions because the blood vessel is located directly ventral to the swim bladder [Fig. 4(e)].

Two significant injuries that are likely to result in eventual mortality, swim bladder rupture and kidney rupture (Stephenson *et al.*, 2010; Halvorsen *et al.*, 2011), are highly correlated with one another (correlation coefficient = 0.71) and so they are plotted together [Fig. 4(d)]. However, neither injury relates simply to the range from the source, nor to the signal level as expressed by peak pressure (Fig. 5). An exception, however, appears to be for ranges less than about 50 m, for which injury rate for rupture of both kidney and swim bladder generally decreases monotonically as range increases [Fig. 4(d)], or decreasing peak pressure (Fig. 5). However, beyond about 50 m, the injury rate increases again reaching a maximum between 100 and 150 m. This effect is examined further in Sec. IV.

B. Acoustic results

Figure 6 provides an overview of acoustic results with respect to range for peak pressure and sound exposure level (SEL) [Fig. 6(a)] and for pressure impulse based on the same data [Fig. 6(b)]. The data are those obtained at each of the exposure test cages. While these data can be expressed in alternate ways, the results in Fig. 6 focus on measures of the acoustic field that might be anticipated to correlate with injuries observed during the experiment.

Thus, with $p(t)$ representing the time series of pressure at any given range, then peak pressure is the maximum of $|p(t)|$ expressed in dB re 1 μ Pa and SEL is the time integral of $p^2(t)$ expressed in dB re 1 μ Pa²-s. These quantities [Fig. 6(a)] decay monotonically with increasing range from the explosive source, as expected, and are furthermore well-described by an empirical equation based on scaled range (Soloway and Dahl, 2014) for which a TNT equivalent weight of 4.66 kg was used (dashed, gray line). The pressure impulse [Fig. 6(b)] decays in the same manner. Here, the cumulative integral of $p(t)$ over time is first computed, and the maximum value is taken as the specific measure of pressure impulse.

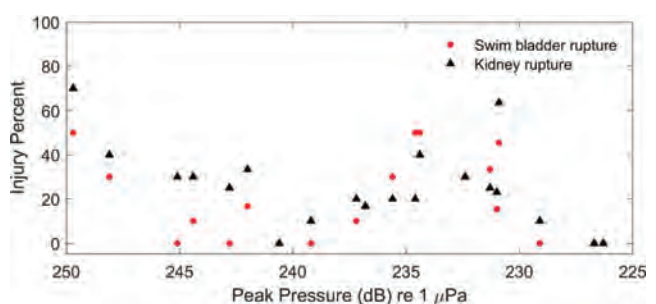


FIG. 5. (Color online) Pattern of percent injury for swim bladder rupture and kidney rupture originally shown in Fig. 4(d) as function of range displayed but here as a function of peak pressure. [Note error bars not shown to emphasize pattern but they are identical to those in Fig. 4(d).]

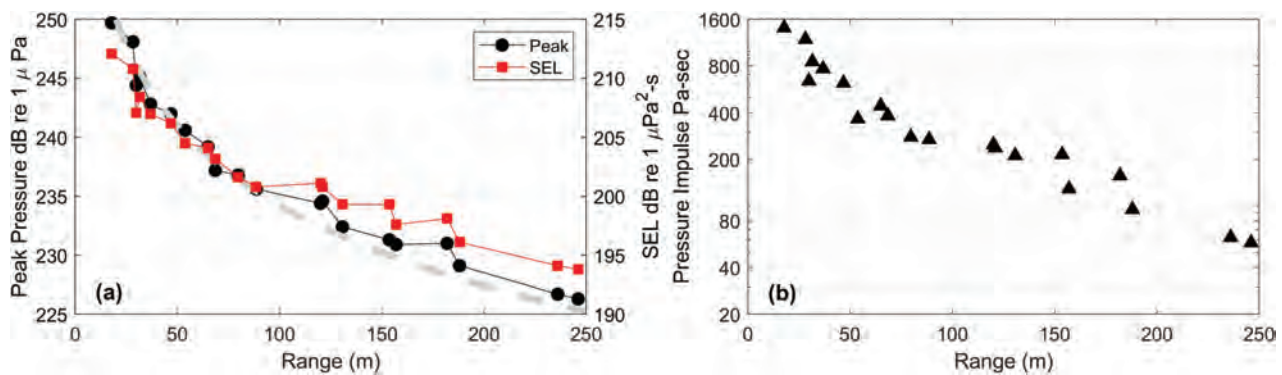


FIG. 6. (Color online) (a) Peak pressure and SEL for all 20 cages as a function of range from the explosive source over the four trials. Dashed-gray line is scaled-range based empirical prediction of peak pressure. (b) Pressure impulse from the same data.

IV. DISCUSSION

Results from this study, while limited to a single species and environment, provide new and important insight into potential physical effects of sound from explosions on fishes in open water. The results demonstrate that damage to Pacific sardines exposed within 50 m of the source decreases with increasing range. However, the results also lead to the suggestion that some effects do not necessarily support the expected dose/response relationship between increasing distance (greater than 50 m) and decreasing effect. It is possible that future analyses might demonstrate such a relationship with other species and/or other acoustic conditions.

A. Physical effects

Twelve potential effects were investigated. These were selected based on earlier studies using another impulsive source—pile driving (e.g., Stephenson *et al.*, 2010; Halvorsen *et al.*, 2011; Halvorsen *et al.*, 2012b). As demonstrated in Table I, 7 of the 12 potential effects were either not observed throughout the experiment or did not differ significantly from controls at any distance from the explosion. The remaining five effects, burst capillaries, fat hematoma, reproductive blood vessel rupture, swim bladder rupture, and kidney rupture, were significantly different from controls ($\alpha=0.05$), as shown in Table I and Fig. 4. Thus, data suggest that these were injuries that could be attributed to exposure to the explosion.

It is interesting, but not easily explained, that some tissues, such as the stomach and gut, located near the swim bladder did not show any damage in the study, whereas such damage occurred in the laboratory study of impulsive pile driving (e.g., Halvorsen *et al.*, 2012a; Halvorsen *et al.*, 2012b) for which repetitive exposure of impulsive sound was simulated. While the reason for the differences in findings are not clear, there are several possibilities, including signal level and impulse characteristics such as rise time. It is also possible that more damage on tissue distant from the swim bladder, as the stomach and gut, occurs when there is repetitive exposure, as in the pile driving studies, but not when there is a single exposure, as in the current study.

The proportion of burst capillaries [Fig. 4(a)] was significantly higher within approximately 20 m from the explosion than in the controls (closest cage vs controls $p=0.01$). The burst capillaries were generally noted in the body wall and therefore are not in direct contact with the swim bladder. Thus, it might be plausible to assume that this injury did not result from displacement of the swim bladder walls. While the cause for the burst capillaries is not clear, this is something worth examining in future studies.

Pacific sardines have a prominent blood vessel that traverses the ventral surface of the swim bladder and then splits and runs to the bilateral reproductive organs. Considerable damage occurred to this reproductive blood vessel, although the proportion of fish with this injury [Fig. 4(c)] was lower at the closest ranges. For ranges greater than about 50 m, the degree of this injury correlates well with rates of swim bladder and kidney rupture [Fig. 4(d)]. One explanation as to why this injury was not more frequently observed within 50 m is that the considerable damage to the nearby swim bladder obscured observation of this injury in some animals.

Fat hematoma was observed both in the large adipose deposits in the body cavity as well as on fatty connective tissue around the swim bladder. As shown in Fig. 4(b), fat hematoma was seen in fish exposed at every distance (Table I: between treatment heterogeneity $p=0.394$). The presence of fat hematoma over all distances at which fish were exposed means that, at least at this time, we cannot establish an onset of injury based on the ranges tested in this study. Moreover, the physiological significance of fat hematoma is not clear at this time. We speculate that large deposits of fat in the experimental subjects may be the result of excess feeding and may not be present in wild Pacific sardines, which in turn could reduce the prevalence of this injury in the wild.

Perhaps the most significant finding is for the swim bladder and kidney. While the initial hypothesis in this study was that results would show a decrease in effects at increasing distance from the source, this was not the case for these organs. Instead, results show that both organs had considerable injury in fish exposed within approximately 50 m of the source in this study. Fewer injuries were observed between about 50 and 125 m, as might be predicted from a close relationship between received signal level and damage.

However, results also showed a second region of extensive injury to the swim bladder and kidney from approximately 125 to 150 m, while beyond that distance, and between 200 and 250 m, the level of swim bladder and kidney rupture decreased to zero. In the case of these injuries, the non-monotonic pattern of injury rate evident between 125 and 150 m is a notable result of this study. The proposed mechanisms for this pattern are discussed below.

B. Properties of the underwater acoustic waveguide and detailed inspection of waveforms incident on the caged fish

In previous studies of the effects of explosives and impulse-like anthropogenic sounds on fishes, peak pressure and pressure impulse (Yelverton *et al.*, 1991; Govoni *et al.*, 2003; Govoni *et al.*, 2008), and SEL (e.g., Casper *et al.*, 2012; Halvorsen *et al.*, 2012a) were used as measures of dosage for proximate exposures. Thus, it was anticipated that injury observations in this study (Fig. 5) would show a similar trend with blast strength or distance that mirrors the acoustic data (Fig. 6). However, results [Fig. 4(d)] show that the probability of the major physical impacts (kidney or swim bladder rupture) is high within 20 to 30 m of the source, decreases to a low in the 50 to 70 m range, and then increases again between 120 and 150 m, before declining

beyond about 150 m. Thus, while these results do not correlate directly with either peak sound level or SEL (at least beyond about 30 m), a plausible explanation for the pattern of injury with range in Fig. 4(d) is related to properties of an underwater acoustic waveguide that govern the experiment.

The averaged sound speed conditions [Fig. 7(a)] indicated a mild downward refracting sound speed profile owing to a thermocline, and five eigenrays are computed [Fig. 7(b)] using ray theory connecting the source at depth 10.5 m to a cage at depth 10.9 m, range 154 m, representing the dominant contribution at this range. The influence of refraction is best seen in the direct path (1) showing slight downward refraction at 154 m. Other dominant paths are the bottom reflected (2), surface reflected (3), and two multiple surface/bottom reflected paths (4).

For the most part, the first three paths carry the majority of the energy from the explosive source, with the influence of bottom reflection on path 2 changing over range depending on the bottom grazing angle θ , which, for this example, is about 7° . The effect of reflection from the seabed at angle θ is assessed by way of the plane wave reflection coefficient, for which the magnitude and phase is displayed in Fig. 7(c). Here, the computation is based on a sediment sound speed of 1670 m/s, sediment density of 1800 kg/m^3 , and sediment attenuation of $0.5 \text{ dB}/\lambda$, values that are within the ranges

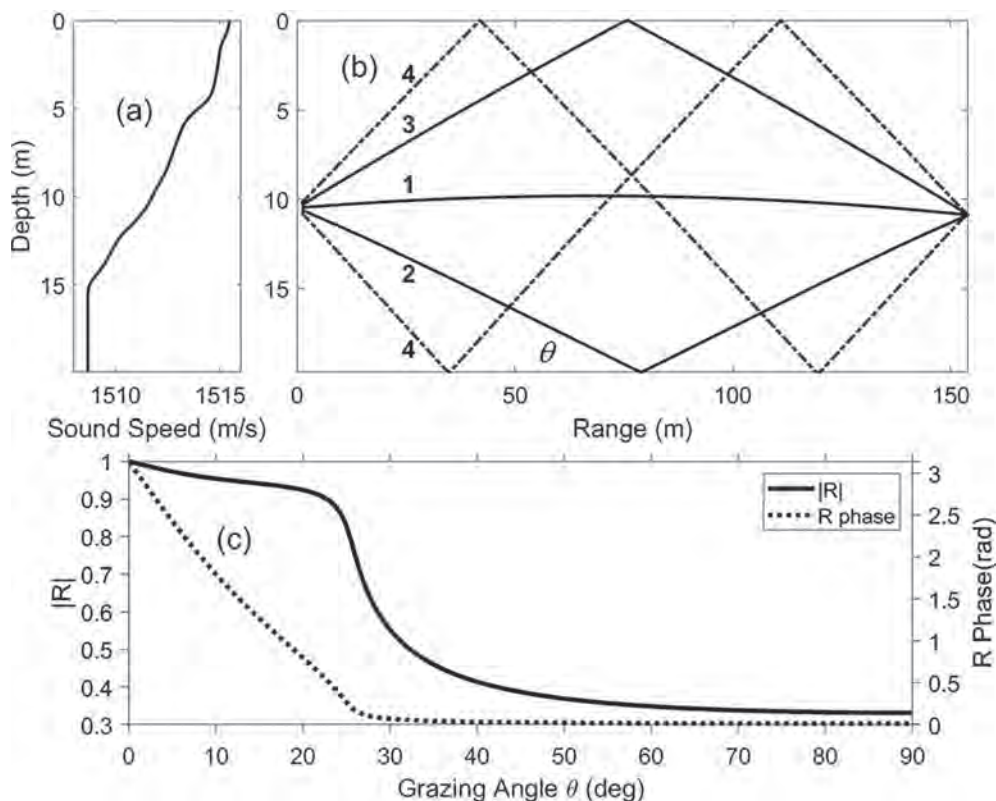


FIG. 7. (a) Sound speed versus depth averaged over the four trials. (b) Ray paths for dominant eigenrays connecting source at depth 10.5 m to receiver at depth 10.9 m and range 154 m, computed using ray theory and the sound speed profile shown in (a). Paths shown by solid lines are of higher amplitude relative to paths shown by dashed lines. Integers correspond to the ray paths as follows: 1, direct path; 2, bottom reflection; 3, surface reflection; and 4 represents two multiple surface/bottom reflections. (c) Magnitude (solid line) and phase (dotted line) of the plane wave reflection coefficient based on the nominal descriptors for a sandy seabed that characterizes the area. See text for detailed explanation.

of observations made from sandy sediments (Yang and Tang, 2017).

Alternate descriptors for the seabed are also possible, but the basic properties displayed in Fig. 7(c) will not change significantly, and in particular, the critical angle delineating the angle below which there is near-total reflection is near 21° . Thus, for the example, for a range of 154 m, the magnitude of the reflection coefficient $|R|$ for the bottom reflected path will be nearly 1, with the reflection coefficient having a substantial phase angle. Some implications of this phase are discussed further in the Appendix.

Figure 8 shows pressure waveforms measured at 28, 68.5, and 154 m from the source detonation. The full measurement bandwidth (1 MHz) version is shown by a thin black line and a low-pass (5 kHz) version by a thick gray line. Note that the 7-ms period of each graph contains the primary arrival structure and energy. Beyond this 7-ms time period, a first, second, and in some cases a third, bubble pulse can be observed at successive delays of about 250 ms, as would be notionally predicted for an explosive charge at this depth and weight (Chapman, 1985).

At 28 m [Fig. 8(a)], the average of the swim bladder and kidney injury rate is 35% [see Fig. 4(d)], and the maximum observed peak pressure and SEL are 247 dB re $1 \mu\text{Pa}$ and 208 dB re $1 \mu\text{Pa}^2\text{-s}$, respectively. The direct path (1) and bottom-reflected path (2) are separated by about 4 ms, with amplitude of path 2 reduced to about 40% compared with path 1, which is nominally consistent with the magnitude of the reflection coefficient [Fig. 7(c)] evaluated at grazing angle 35° . Approximately 1-ms later, the sea surface-reflected path (3) arrives and abruptly reduces the pressure. Referring to the full band version, the sequence of sharp spikes at (3), the first of which is negative, is assumed to identify the leading edge of the surface reflected pulse before the onset of cavitation (Wentzell *et al.*, 1969). The smoothed (5 kHz) version of the data shows the waveform reaching a negative pressure of about -100 kPa .

At 68.5 m [Fig. 8(b)], the average of the swim bladder and kidney injury rate falls to 15%, and the maximum observed peak pressure and SEL are 238 dB re $1 \mu\text{Pa}$ and 202 dB re $1 \mu\text{Pa}^2\text{-s}$, respectively. The sequence of arrivals 1-2-3 is compressed because of the longer range, so paths 1

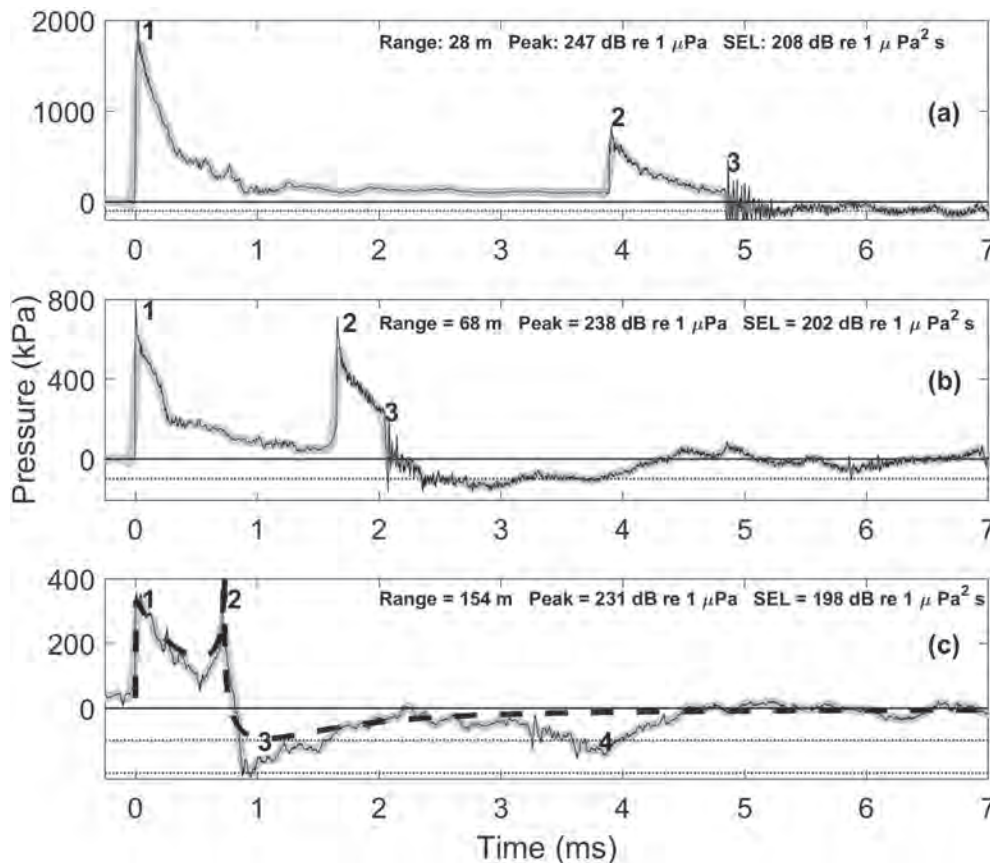


FIG. 8. (a) Time series of peak pressure in kPa measured at range 28 m from the source. The thin black line is original data at 1 MHz bandwidth while thick gray line is a low-pass (5 kHz) version. The numbers 1, 2, 3 identify arrivals of the direct path, bottom reflected path, and sea surface reflected path, respectively [see Fig. 7(b)]. Cavitation onset from the sea surface is indicated by the highly oscillatory behavior seen in the full bandwidth data (also see text), which stabilizes to approximately -100 kPa in the low-pass result; the black solid and dotted lines identify 0 and -100 kPa reference lines, respectively. (b) Same as (a) but measured at range of 68 m. (c) Same as (a) but measured at range of 154 m with a third reference line, -200 kPa , shown and an additional number, 4, identifies two multiple surface, bottom reflected arrivals that arrive at nearly the same time. Black, dashed line represents model for direct and bottom reflected paths as discussed in the Appendix.

and 2 are now closer in amplitude as might be anticipated by the grazing angle of $\sim 18^\circ$. Arrival of path 3 about 0.5 ms after arrival of the bottom reflected path 2 [predicted by ray theory using the sound speed profile of Fig. 7(a)] represents an excellent example of the cavitation surface cut-off effect (as in Wentzell *et al.*, 1969).

Finally, at 154 m [Fig. 8(c)], the average of the swim bladder and kidney injury rate has risen to 30% though the peak pressure and SEL have decayed and are 231 dB re 1 μPa and 198 dB re 1 $\mu\text{Pa}^2\text{-s}$, respectively. The sequence of arrivals 1-2-3 is further compressed and, importantly, negative pressure has now reached about -200 kPa, falling to the value in a distinctly more rapid manner than observed at the other two ranges.

A simplified model curve (dashed line) is also shown, but it is limited to the portion of the explosive waveform associated with paths 1 and 2. Derivation of this line is given in the Appendix, but the key point is that the bottom reflected path, by itself and without contribution from the negative reflection from the sea surface, leads to substantial negative pressure of about -100 kPa, to which the contribution from the sea surface is expected to push this further toward -200 kPa.

Not all waveforms associated with the four tests conducted at five ranges display the above properties of negative pressure, insofar as (i) low-pressure point and (ii) rate of pressure change, versus range as clearly as the examples in Fig. 8. However, the examples in Fig. 8 do capture the sense of the acoustic data, and show a roughly similar relation with other data within the approximate range interval 100–175 m, which aligns with the increased injury rate for both the strongly correlated ruptured swim bladder and ruptured kidney injuries [Fig. 4(d)].

Finally, it is important to reiterate that these specific acoustic waveguide results depend on bottom properties similar to those in this study and, to some extent, to a similar water depth. While the same general waveguide effects may be seen in other environments, the results reported here cannot be extrapolated to other depths and bottoms without a fuller understanding of the effects in a broader range of environments.

C. Mechanisms of physical effects

There is growing agreement in the literature that much of the internal physical damage from exposure to impulsive acoustic stimuli is a result of the interactions between the gas-filled swim bladder in the abdominal cavity and the nearby (and often contacted) soft tissues such as the kidney (e.g., Goertner *et al.*, 1994; Carlson, 2012; Halvorsen *et al.*, 2012a; Carlson *et al.*, 2019). This observation is supported by findings that physical effects from exposure to impulsive pile driving, similar to those seen in this study, were found in fishes with a swim bladder, and not in a species without a swim bladder (Halvorsen *et al.*, 2012a). Similarly, a study of injuries to fishes without a swim bladder that were exposed to an explosion also showed fewer physical effects

compared to fishes with swim bladders (Goertner *et al.*, 1994). Further supporting this argument, it is important to note that the greatest injury in the current study was to the swim bladder as well as to the kidney and reproductive blood vessel, which lie dorsal to and ventral to the surface of the swim bladder, respectively.

Following from the idea of swim bladder involvement, the acoustic analysis leads to the suggestion that, at a range of 154 m (this being a specific example), the greater rate of pressure change and deeper low-pressure point during the decompression phase are linked to swim bladder expansion damage and rupture. This includes damage to immediately neighboring organs as manifested by the kidney data that are highly correlated with the swim bladder data. This is the proposed cause of the observed higher injury rate at 154 m despite the higher peak pressures observed at 68 m, and has been suggested by earlier models of swim bladder related injury (Goertner, 1978; Wiley *et al.*, 1981).

To see how this can happen, the acoustic pressure data of Fig. 8 is converted to absolute pressure by adding one atmosphere (101.3 kPa) plus the depth-dependent hydrostatic pressure (105.5 kPa based on measurement depth of 10.5 m). Thus, we assume a static pressure P_A of 206.8 kPa, and the low pressure the fish were subject to, or minimum decompression pressure P_D , is estimated to be 106, 81, and 7 kPa at respective ranges 28, 68, and 154 m (Fig. 8). These estimates were based on the smoothed, low-pass version of the data (Fig. 8) upon adding P_A .

For a constant temperature, Boyle's law puts the ratio of swim bladder volume at maximum decompression V_{Dmax} compared with that at the acclimation (or static) pressure V_A equal to ~ 2 , 2.5, and ~ 30 for the same increasing range set, and it can be assumed that swim bladder tissues (and any other air-filled tissues) have undergone considerably more strain at range 154 m. Note that the issue of swim bladder tissue compliance is beyond the scope of this study, and thus we assume that pressure reduction has produced a volume expansion that is instead bounded by Boyle's law. For example, Stoyek *et al.* (2011), in a study of tissue compliance, showed that Boyle's law predicted well the volume changes in the swim bladder of zebrafish (*Danio rerio*) during compression but had an upper bound during expansion.

That being said, it is interesting that Brown *et al.* (2012) also determined that the main factor associated with the mortal injury of juvenile Chinook salmon during their study on simulated turbine passage was the ratio between the acclimation pressure and the lowest exposure pressure, this being the same ratio as defined above.

A possible related explanatory variable is formed upon combining the rate of pressure change and minimum decompression pressures as follows. We take the time derivative of Boyle's law in the form

$$V_D(t) = V_A P_A / P_D(t), \quad (1)$$

where the decompression volume $V_D(t)$ and pressure $P_D(t)$ vary with time during the decompression phase, which gives

$$\dot{V}_D(t)/V_A = -P_A \dot{P}_D(t)/P_D^2(t), \quad (2)$$

where dot notation for time differentiation is used. Equation (2) describes a volumetric strain rate, or fractional increase in volume per unit time, with dimension 1/s. A means to obtain consistent and robust estimates of both $\dot{P}_D(t)$ and $P_D^2(t)$ from all the raw acoustic data remains under study; however, inspection of smoothed waveforms in (Fig. 8) immediately suggests that for range 154 m [Fig. 8(c)], there is clearly a larger value of $\dot{P}_D(t)$ based on the slope of the pressure decay corresponding to the arrivals of paths 2 and 3, and a smaller value of $P_D^2(t)$, leading to much higher estimate of volumetric strain rate.

A mechanism for damage to the swim bladder or other air-filled voids cannot be attributed solely to high volumetric strain rate nor volume expansion at maximum decompression. For example, this effect would not explain our necropsy observations for ranges less than about 50 m [Fig. 4(d)], a range interval where the three acoustic metrics (Fig. 5) appear to show correlation with injury and are thus more valid explanatory variables. Furthermore, Wiley *et al.* (1981) discuss a mechanism for swim bladder oscillations imparted by the positive-going shockwave. A degree of oscillatory swim bladder response is expected because of the impulsive loading, which could contribute to the effects found at close range. However, in the current study, the continued decay of pressure impulse with range [Fig. 6(b)] is at variance with the injury data once the range exceeds about 50 m, and consideration of rarefaction effects on swim bladder expansion may be more relevant to injury potential.

D. Study species

Teleost fishes use their swim bladder for buoyancy and for maintaining position in the water column with minimal expenditure of energy (e.g., Helfman *et al.*, 2009). Pacific sardines (and all Clupeiformes) are physostomous fishes and periodically go to the surface and gulp air, which they move from the esophagus to the swim bladder via a small pneumatic duct. In the current study, it was not possible to know the ultimate fill status of the swim bladder after the acclimatization period at the experimental depth. The significance of this is that the response of the swim bladder to acoustic stimulation when the fish is at the experimental depth may differ depending on whether it is full, with fully expanded walls, or not. For example, if the walls are not fully expanded, they are less likely to impact surrounding tissues when exposed to an impulsive sound, resulting in less potential damage to surrounding tissues (Halvorsen *et al.*, 2012a).

At the same time, it should be noted that all of the fish cages were observed using an ROV while they were at depth prior to the explosion. The majority of fish were schooling in mid-cage (Fig. 1) and did not appear to show any obvious signs of buoyancy issues (i.e., exerting excess energy to maintain their depth). Thus, it is possible to hypothesize that the swim bladders in the fish was normally inflated for the experimental depth.

The Pacific sardine is representative of what is one of the most commercially important group of fishes in the world, the Clupeiformes (herrings, sardines, and relatives). While it is tempting to extrapolate from this species to other clupeids and fishes in other unrelated taxa, this needs to be done with utmost caution because is not known whether the anatomical and physiological differences between Pacific sardines and fishes in other taxa would also affect how they respond to underwater explosions. While recent work on effects of pile driving sounds shows there is some similarity in effects between species that are morphologically distinct, they also suggest caution in trying to extrapolate from a single species (Halvorsen *et al.*, 2012a; Casper *et al.*, 2017), particularly until there are comparable data to those presented here for a number of anatomically distinct fish species. Such caution also derives from similar concerns about extrapolation between species made in the most recent guidelines for potential effects of sound on fishes (Popper *et al.*, 2014; Popper and Hawkins, 2019).

V. CONCLUSIONS

While the results presented here are for a single species at a single depth, they still provide important insight into potential effects on fishes exposed to sound from explosions. The results also raise important issues with how effects of these sounds should be analyzed in the future. A detailed understanding of the acoustic field as related to water depth, bottom characteristics, and other aspects of propagation are clearly critical.

It is also important to understand that results should only be extrapolated to other species with the greatest caution. Indeed, this study should be thought of as only the first of a number that are needed in order to understand the potential effects of sounds from underwater explosions on fishes. Important variables to investigate in future studies are, among others, different species/morphologies, depth of exposure, different depths of water, and different bottom types. Furthermore, results reported here are likely related to the specific size of the explosion, source and receiver geometry, and other aspects of the acoustic environment.

Moreover, while it is suggested that swim bladder rupture and kidney rupture are mortal injuries, this is still conjecture since animals were euthanized on return to the surface. Thus, it would be important to conduct survival studies where fish are not euthanized and monitored for some period of time after exposure. The only studies which examined survival showed that several species of fish recover from exposure to intense impulsive pile driving sounds (Casper *et al.*, 2012; Casper *et al.*, 2013), while recognizing that subjects were fed and not exposed to predators or adverse environmental conditions during recovery.

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APPENDIX: SIMPLIFIED MODEL FOR PORTION OF THE EXPLOSIVE WAVEFORM INCIDENT ON THE CAGED FISH

A simplified model for the portion of the explosive waveform associated with paths 1 and 2 in Fig. 8(c) is outlined in this appendix. The goal is to capture the primary physics that can assist interpretation of the data and, in particular, show how bottom reflection can amplify negative pressure possibly leading to greater injury.

The analysis applies equations from Chapman (1985), derived from scaled range theory, hereafter referred to as C85, that are governed by range from the source and W , or TNT equivalent weight (4.66 kg). That scaled range applies to this study can be confirmed through inspection of results in Fig. 6(a).

For path 1, or the direct path, the slight curvature caused by refraction is ignored and assume a straight path, putting range $r_1 = 154$ m. The direct path waveform $P_{DP}(t)$ is modeled as an exponential of the form

$$P_{DP}(t) = \hat{P}_{DP} e^{-t/\tau_{DP}}, \quad (\text{A1})$$

where $\hat{P}_{DP}$ is the shock impulse peak pressure amplitude based on C85 Eq. (1), and τ_{DP} is the time constant based on C85 Eq. (12). Note that time $t=0$ in the Eq. (A1) is

referenced to the onset of the direct path as observed at range 154 m, which we take as r_1/c , where c is a depth-averaged sound speed (1513 m/s).

Path 2, due to bottom reflection, is a most interesting feature of this study. As a first step, the peak pressure $\hat{P}_{BP}$ and time scale τ_{BP} for a bottom-reflected path are also modeled as in Eq. (A1), where, in this case, the range is set equal to the total extent of path 2, call it r_2 , again taken as a straight ray path determined by the geometry.

The bottom reflected pulse is further modified by the reflection coefficient R . It is emphasized that, in line with the simplicity of this model, R is derived from the plane wave reflection coefficient [Fig. 7(c)] from a sediment half-space, which is independent of frequency. Referring now to Fig. 7(c), the bottom grazing angle θ for path 2 is $\sim 7^\circ$, which puts $|R| \sim 0.94$ (about 0.5 dB of reflection loss) with phase equal to about 2 radians. The small grazing angle, well inside the critical angle of 21° , provides some additional justification for using the plane wave reflection coefficient. For closer ranges, and in particular ranges in the vicinity of the critical angle, a more complex spherical wave reflection formulation (Westwood, 1989) would likely be necessary.

Given the pressure field of high bandwidth incident on the seabed, it is expected that the substantial phase angle will distort the bottom-reflected pulse (Cron and Nuttall, 1965). Let $R(\theta)$ be the complex reflection coefficient evaluated at $\theta = 7^\circ$ with both magnitude and phase given in the preceding paragraph; then to embody the effects of complex-valued reflection coefficient in the bottom reflected path, we employ a Hilbert transform as follows:

$$P_{BP}(t) = \text{Re} \left\{ H(\hat{P}_{BP} e^{-t/\tau_{BP}}) R(\theta) \right\}, \quad (\text{A2})$$

where H represents the Hilbert transform and time $t=0$ is referenced to the onset of the bottom-reflected path equal to r_2/c .

The two contributions Eqs. (A1) and (A2) are added, with the latter delayed by time r_2/c . This gives the model curve shown in Fig. 8(c), which captures the sense of the combination of the direct and bottom reflected arrival. It is seen that bottom reflection at this range, by itself, produces a distorted pulse with sharper peak, a faster decay towards negative pressure, and substantial negative pressure to which additional negative pressure originating from the sea surface will be added.

Note that similar but more detailed modeling of the explosive waveform limited to short ranges and without boundary reflections is found in Wilson *et al.* (2019). Key differences between this study and that of Wilson *et al.* are that here the bubble pulse contribution is not included for the reason discussed in the context of Fig. 8, and for further simplicity a single time scale τ_{DP} is used.

¹For more information, see www.hstteis.com.

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Estimation of seabed properties and range from vector acoustic observations of underwater ship noise

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Estimation of seabed properties and range from vector acoustic observations of underwater ship noise

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Abstract: The Intensity Vector Autonomous Recorder (IVAR) simultaneously measures acoustic particle velocity and pressure. IVAR was deployed during the 2017 Seabed Characterization Experiment (SBCEX) with the primary objective to study sound propagation in fine-grained, muddy sediments. In this study a Bayesian inversion framework is applied to ship underwater noise recorded by IVAR. The data are relative phase of pressure and vertical particle velocity, a quantity that is independent of the ship noise source spectrum. Inversion estimates for the sediment layer and underlying basement properties are in agreement with other reports from SBCEX. © 2020 Acoustical Society of America

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1. Introduction

The Seabed Characterization Experiment (SBCEX) was conducted over the so-called New England mud patch, located about 100 km south of Cape Cod, MA, during March–April 2017, with the primary objective to study sound propagation in fine-grained, muddy sediments. Emerging results from SBCEX based on differing acoustic measurement methodologies¹ are in agreement on key sediment properties: a layer of fine-grained sediment of order 10 m thick starting at the water–sediment interface with an upper sediment sound speed nearly equal to or slightly less than the sound speed at the water–sediment interface,^{2–6} with layer thickness diminishing on the periphery.⁷ These results are largely consistent with the extensive stratigraphic analysis of the area by Goff *et al.*⁸ using chirp sonar.

In this study, vector acoustic properties of underwater noise from a cargo ship traversing the central region of the SBCEX area are analyzed and inverted for sediment characteristics using a Bayesian approach, for which the model space is limited to the aforementioned layer thickness and sound speed, and an underlying basement sound speed. Observations were made with a vector sensor; vector field properties relating to the phase of pressure and vertical particle velocity are used as input for the geoacoustic inversion.

2. Data description

Recordings from the Intensity Vector Autonomous Recorder (IVAR) made on March 8 (20:53–21:53 UTC) captured the transit of the M/V *Alice Oldendorf* (IMO number: 9183776, length: 190 m). This IVAR deployment from the R/V *Endeavor* during leg 1 of SBCEX was at 40.4716°N, 70.6061°W, where the mean water depth during the transit was 75.5 m as measured by IVAR.

Acoustic particle velocity along three axes and pressure were recorded coherently in four channels, at 1.25 m above the seabed. IVAR system details are given in Dahl and Dall'Osto,⁹ which discusses measurements from explosive sound sources made at the second SBCEX deployment site, about 3.2 km northwest from this location. Ship noise recordings were made on the four high-gain (30 dB) channels of IVAR, while those involving explosive sources used the four low-gain (0 dB) channels.

The data are expressed in the frequency domain, formulated by the Fourier transform of each channel over identical 1-s data windows. These define, for example, $S_p(f; t)$ and $S_{v_z}(f; t)$ as the complex spectra for pressure and the vertical component of particle velocity, respectively. The potential energy spectrum is thus $(1/2\rho c_w^2)\langle |S_p(f; t)|^2 \rangle$ based on water density ρ of 1027.6 kg/m³ and mean water sound speed c_w of 1468.3 m/s, with angle brackets denoting a 10-s moving time average. Similarly, the kinetic energy spectrum is $(\rho/2)\sum_{i=1}^3\langle |S_{v_i}(f; t)|^2 \rangle$, where i represents the x , y , z components of particle velocity.

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Spectrograms of the potential [Fig. 1(a)] and kinetic [Fig. 1(b)] energy density corresponding to the transit of the M/V *Alice Oldendorf* each illustrate an interference field pattern. The time-vector is aligned for $t=0$ s to be at the closest-point-of-approach (CPA) to IVAR, ~ 2470 m, based on the ship's Automatic Identification System (AIS). The received noise level increases slightly as the vessel opens in range after CPA, presumably owing to greater stern-aspect noise radiation. Note that the 1-h time average of kinetic and potential energy density is within 1 dB over the approximate bandwidth ~ 25 –200 Hz.

The active intensity bearing¹⁰ is derived from the pressure and the horizontal (x, y) component of particle velocity, and the direction of arrival [Fig. 1(c)] is 180° from the arc-tangent of these two orthogonal active intensity measures, rectified by the IVAR internal compass (x -channel oriented along bearing 199°). A robust, single estimate of direction-of-arrival versus time is obtained by a frequency average over the band 30–120 Hz.

An additional detail is provided by the cross-spectrum $\langle S_p(f; t) S_{v_z}^*(f; t) \rangle$, where $*$ indicates complex conjugation. The phase pattern of this quantity [Fig. 1(d)] reveals cutoff frequencies for modes, and has been shown to be informative in vector acoustic observations of ship noise.¹¹ These data are used in the inversion process, where phase is given by the inverse tangent of the ratio of imaginary to real parts of $\langle S_p(f; t) S_{v_z}^*(f; t) \rangle$. For the inversion, however, the absolute value of phase is used because phase magnitude is a more robust quantity that avoids rapid $\pm\pi$ swings, which are difficult to model precisely. In the following, a data vector $\mathbf{d}$ is defined as the absolute value of the phase (normalized by π) at a given time t for frequencies 30–120 Hz every 1 Hz. Frequencies 86–88 Hz are eliminated from $\mathbf{d}$ owing to electronic contamination, setting the length $\mathbf{d}$ equal to 88.

3. Forward modeling and geoacoustic inversion

3.1 Forward modeling

The forward model used in the Bayesian inversion is based on the sum of normal modes for acoustic pressure and particle velocity. An analogous approach⁹ is developed for single modes applicable to cases where geometric dispersion is sufficient to identify separated modes. The complex spectral component of pressure $P(f)$ received at range R and receiver depth z_r is expressed as

$$P(f) \approx S_0(f) \sum_n \frac{e^{ik_n R - i(\pi/4)}}{\sqrt{k_n R}} U_n(z_s, f) U_n(z_r, f), \quad (1)$$

where U_n is the n th vertical mode function at frequency f , k_n is the corresponding horizontal wavenumber (computed using the Kraken normal mode program¹²), z_s is source depth, z_r is

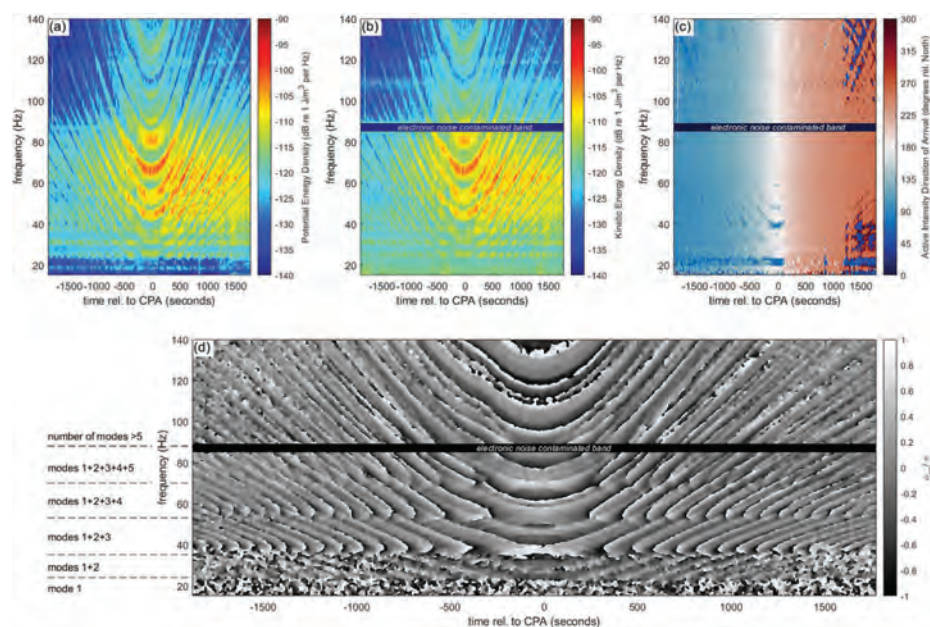


Fig. 1. (Color online) (a) Potential and (b) kinetic energy density recorded during the transit of the M/V *Alice Oldendorf*. (c) Active intensity directional of arrival. (d) Phase cross-spectrum between pressure and vertical particle velocity revealing approximate cutoff frequencies for modes as suggested by horizontal dashed lines, e.g., mode 3 emerges at frequency 35 Hz. Time for (a)–(d) is relative to the CPA.

receiver depth (fixed to the IVAR sensor depth of 1.25 m above the seabed), and the asymptotic representation for the Hankel function is used where R is range. An unknown source spectrum $S_0(f)$ is shown for completeness, but is ultimately eliminated from the model upon taking a ratio.

Horizontal and vertical derivatives of Eq. (1) yield the corresponding horizontal $V_r(f)$ and vertical $V_z(f)$ particle velocities, respectively. For $V_r(f)$ the mode sum includes the factor $(k_n/2\pi f\rho)$, where a second term in $V_r(f)$ associated with the horizontal derivative becomes negligible compared with the first term for ranges greater than a few wavelengths and is thus ignored. For $V_z(f)$ it is $U_n(z_r, f)$ in the mode sum that is replaced by a finite difference approximation for the vertical derivative evaluated at z_r and multiplied by $(i/2\pi f\rho)$.

From these quantities the potential E_p and kinetic E_k energy density are formed as

$$E_p(f) = \frac{1}{4} |P(f)|^2 / (\rho c_w^2), \quad (2)$$

$$E_k(f) = \frac{1}{4} \rho (|V_r(f)|^2 + |V_z(f)|^2), \quad (3)$$

and complex vertical intensity as

$$I_z = \frac{1}{2} P(f) V_z^*(f), \quad (4)$$

from which the real part yields active vertical intensity $I_z(f)$ and the imaginary part reactive vertical intensity $Q_z(f)$.

There are multiple options to proceed toward a modeled quantity that is independent of the source spectrum. One is via the ratio of $I_z(f)$ to $E_p(f) + E_k(f)$, which was developed as an inversion metric for observations that support resolved single mode arrivals.⁹ Another, used recently for inversion from an active source,¹³ is the vertical phase gradient of acoustic pressure, which is equivalent to the ratio $I_z(f)$ to $E_p(f)$ multiplied by $(2\pi f/4c_w^2)$. The approach used here takes the absolute value of the phase of I_z normalized by π , which corresponds to the data vector. This is computed for the same 88 frequencies as **d**, based on a given geoacoustic parameter vector **m**, and defines the model vector **d(m)** representing a simulated replica of the data.

3.2 Geoacoustic inversion

Geoacoustic inversion is undertaken for which the unknown parameters are fine sediment layer depth H_{sed} , a constant sound speed within this layer c_{sed} , and sound speed of an underlying half-space c_{base} . A combination of uniform prior bounds for these parameters (Table 1) and equidistant grid search space in each model dimension is used in the forward modeling. Additional required parameters were pre-set to streamline the inversion because experimentation suggests these parameters are poorly resolved. These are sediment density set to 1.6 g/cm^3 , to represent a $1.5\text{--}1.7 \text{ g/cm}^3$ range reported in gravity coring operations from SBCEX;¹⁴ sediment attenuation based on a fit to viscous grain shearing theory¹⁵ applicable to the inversion frequency range 30–120 Hz; a basement density that depends on c_{base} following Hamilton,¹⁶ translating to $1.7\text{--}2.1 \text{ g/cm}^3$ for the range of c_{base} values used, and basement attenuation set to $0.6 \text{ dB}/\lambda$. Constant water depth and sound speed (c_w) were taken as 75.5 m and 1468.3 m/s, respectively.

Additionally, range and source depth are unknown and this search space is assessed with little computational cost using the mode-based forward model. Source depth is uniformly sampled between 1 and 20 m in 1-m increments, and range is sampled between 1000 and 4000 m in 5-m increments. (This range extent can be reduced to ~ 200 m upon invoking prior information on range provided by AIS data, but our interest is in keeping range as an unknown parameter.)

The inversion is placed within a Bayesian framework¹⁷ leading to the probability density function (PDF) $P(\mathbf{m}|\mathbf{d})$, representing the conditional PDF for model parameters **m** given the experimental data **d**.¹⁸ This equals the conditional PDF for the data given the model $P(\mathbf{d}|\mathbf{m})$ multiplied by an *a priori* PDF for the model parameters $P(\mathbf{m})$, assumed in this study to be a uniform

Table 1. Inversion geoacoustic parameters list, uniform over given search bounds, and final inversion estimates. Final estimates represent the median MAP over the 21 different range inversions about the CPA and uncertainty σ is based on mixture PDFs as discussed in text. A basement density of 1.9 g/cm^3 corresponds to the estimate $c_{\text{base}} = 1800 \text{ m/s}$.

Parameter	Unit	Search bounds	Median MAP	σ
c_{sed}	m/s	$[0.985, 1.05]c_w$	$1.007c_w$	$0.009c_w$
H_{sed}	m	$[7.0, 11.5]$	9.4	0.27
c_{base}	m/s	$[1700, 2025]$	1800	17

distribution within the selected parameter bounds.¹⁹ Key steps then follow closely Eqs. (15)–(17) from Bonnel *et al.*,²⁰ here, put the model–data mismatch column vector $\mathbf{r} = \mathbf{d} - \mathbf{d}(\mathbf{m})$, and find the data misfit function $E(\mathbf{m}) = (N_f/2) \log_e \mathbf{r}^T \mathbf{r}$, with $N_f = 88$, which, given the established $P(\mathbf{m})$ leads directly to $P(\mathbf{m}|\mathbf{d})$. One-dimensional (1D) marginal PDFs for the geoacoustic model parameters (including the range and source depth), are found upon integrating $P(\mathbf{m}|\mathbf{d})$ over the appropriate model dimensions.

3.3 Geoacoustic inversion results

Figure 2(a) presents estimated values (circles) of the phase magnitude of the cross-spectrum between pressure and vertical particle velocity at CPA compared with a model (Sec. 3.1) based on the maximum *a posteriori* (MAP) estimates²⁰ for H_{sed} (9.4 m), c_{sed} (1499 m/s), and c_{base} (1825 m/s). The MAP estimate for range is 2380 m and for source depth is 3 m. We note that the model–data errors in Fig. 2(a) are approximately uniform across the inversion frequency band, and can be approximated by a Gaussian distribution.

We next invert data from 21 ranges spaced equally over a 20-min period centered about the CPA, with each inversion providing a new $P(\mathbf{m}|\mathbf{d})$ and set of MAP estimates. Each $P(\mathbf{m}|\mathbf{d})$ yields 1D marginal PDFs for the inverted parameters. To evaluate uncertainty we derive mixture²¹ 1D PDFs [Figs. 2(b)–2(d)], based on a weighted linear combination of the 21 1D PDFs (representing component densities) with uniform mixing proportion equal to 1/21. The median values of the 21 MAP estimates, and the standard deviations based on the mixture 1D PDFs, constitute our final inversion estimates and uncertainty, respectively (Table 1).

Finally, it is of interest to invert just for range (including source depth) using the final inversion estimates (Table 1) as known geoacoustic parameters. Here, a longer transit period is studied for which the range between the M/V *Alice Oldendorf* and IVAR varies from the CPA at ~ 2.4 km to ~ 7.5 km. Source depth is again uniformly sampled between 1 and 20 m, and range is now sampled between 1000 and 8000 m. The direction of arrival associated with each 10-s data vector [Fig. 1(c)] is combined with the inversions for range to construct the ship trajectory. The results (Fig. 3), plotted over a map of two-way travel time (twtt) of mud layer thickness,⁸ show correspondence between inverted range and computed bearing, and the AIS data. The 20-min period from which the geoacoustic parameters are estimated is indicated by the 21 triangle symbols, and here propagation paths between the ship and IVAR tend to traverse a relatively constant twtt regime of 12–13 ms. Interestingly, the propagation paths associated with the far west and east portions of the longer transit period appear to interact, respectively, with sediment characterized by a somewhat thinner and thicker mud layer, motivating a future study on seabed variation. The inversion necessarily yields an estimate of source depth with MAP estimates more variable but consistently confined to less than 10 m.

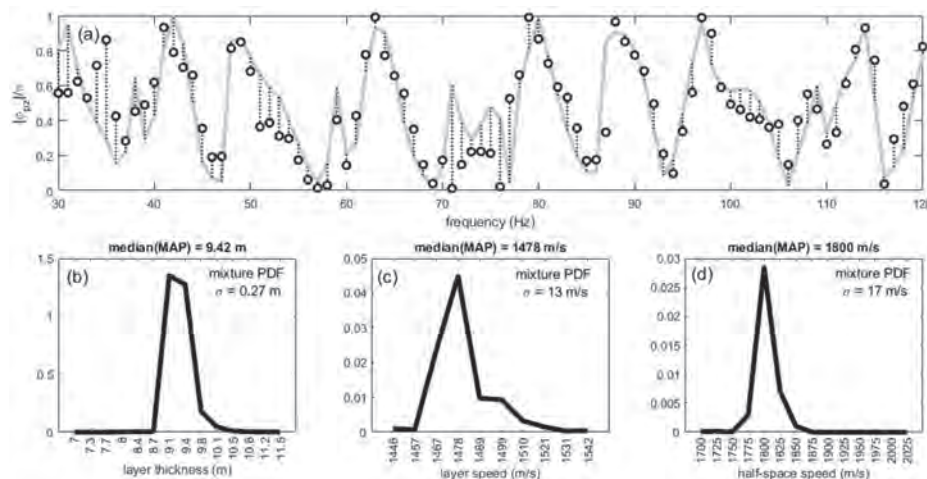


Fig. 2. (a) Phase magnitude of the cross-spectrum (normalized by π) between pressure and vertical particle velocity at CPA (black circles) compared with modeled (gray line) MAP estimates for H_{sed} (9.4 m), c_{sed} (1499 m/s), and c_{base} (1825 m/s), along the MAP estimate for range 2380 m, and source depth 3 m. (b) Mixture 1D PDF for sediment thickness H_{sed} based on inversion of 21 ranges equally spaced over the 20-min observation period and weighted linear combination of the 21, 1D PDFs; listed are the average of the 21 MAP estimates and standard deviation computed from the mixture 1D PDF. (c) Same display for layer speed, c_{sed} . (d) Same display for c_{base} .

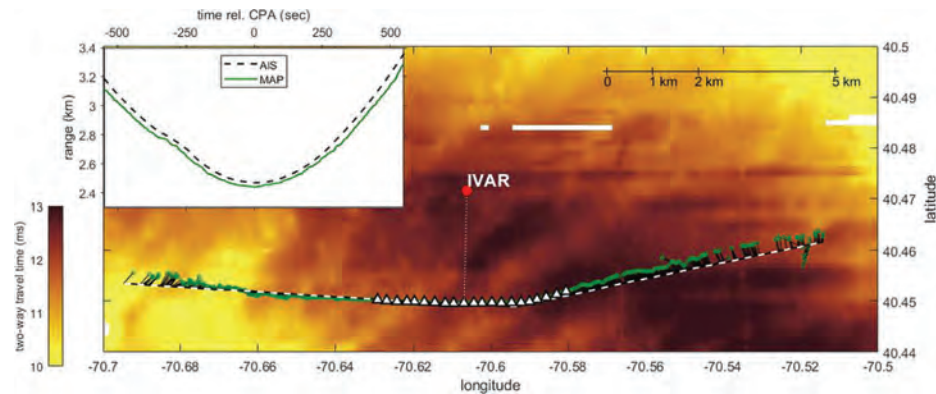


Fig. 3. (Color online) The ship track of the M/V *Alice Oldendorff* as it transits from east to west (dashed line is ground truth from AIS) and estimated from IVAR vector intensity data (green circles). The IVAR estimates include range via inversion, and bearing via inspection of active intensity, as per Fig. 1(c). Geoacoustic estimates are made at 21 locations (triangle symbols) to establish the mean environment (Table 1) for range estimation. Background color corresponds to the twtt measured during a chirp sonar survey of the area (Ref. 8), and inset shows detail of AIS and MAP range estimates over the inversion regime. Background data as plotted here provided courtesy John Goff.

4. Conclusion

This paper applies a Bayesian framework for geoacoustic inversion of the relative phase of pressure and vertical particle velocity of ship noise, a quantity independent of noise source spectrum, observed during the SBCEX conducted about 100 km south of Cape Cod in waters of depth ~ 75 m. A layer of fine-grained, muddy sediment is a distinctive feature of the SBCEX experimental area, and the focus of this study. The results reported here are in agreement with emerging results reported by SBCEX investigators, in particular the sediment layer thickness of ~ 9.4 m and sound speed of ~ 1478 m/s within the layer. A sound speed gradient could not be resolved in preliminary studies and thus was not included in the model space, but a corresponding sediment layer interval velocity of 1.007 (based on c_w) does not rule out a gradient. In addition, the inversion provides credible estimates of ship range and bearing (available through inspection of the angle of horizontal active intensity), both verified by AIS data.

Acknowledgments

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Vector Acoustic Analysis of Time-Separated Modal Arrivals From Explosive Sound Sources During the 2017 Seabed Characterization Experiment

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Abstract—The Intensity Vector Autonomous Recorder (IVAR) is a system that records four coherent channels of acoustic data continuously: one channel for acoustic pressure and three channels associated with a triaxial accelerometer from which acoustic particle velocity is obtained. IVAR recorded the vector acoustic field in broadband signals originating from Signal, Underwater Sound (SUS) (Mk-64) charges deployed at 5–13-km range from the fixed IVAR site (mean depth 74.4 m) as part of the 2017 Seabed Characterization Experiment (SBCEX) designed to study the acoustics of fine-grained muddy sediments. Sufficient geometric dispersion at these ranges permitted unambiguous identification of up to four modes as a function of frequency for frequencies less than 80 Hz. From time–frequency analysis of the dispersed arrivals, a single mode (n) and single-frequency (f_i) properties are identified at peaks in the narrowband scalar field, with time dependence corresponding to mode group speed. At these time–frequency addresses, four quantities derived from the vector acoustic measurements are formed by coherent combination of pressure and velocity channels: first, modal phase speed; second, circularity, a measure of the normalized curl of active intensity; third, depth-dependent mode speed of energy; and fourth, vertical component of reactive intensity normalized by scalar intensity. A means to compute these quantities theoretically is provided, and a comparison of model results based on a notional geoacoustic representation for the SBCEX experimental area consisting of a single low-speed mud layer over a half-space area versus a Pekeris representation based on the same half-space shows a striking difference, with the field observations also clearly at variance with the Pekeris representation. A fundamental property of mode 2, observed at the IVAR location, is a change in sign for circularity and vertical reactive intensity near 37 Hz that is posited as a constraint observation for mode 2 that must be exhibited by any geoacoustic model that includes a low-speed mudlike layer applied to this location.

Index Terms—Acoustic particle velocity, active intensity, circularity, group speed, modal speed of energy, phase speed, reactive intensity, vector acoustics.

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I. INTRODUCTION

THE Intensity Vector Autonomous Recorder (IVAR) is a system that records four coherent channels of acoustic data continuously: one channel for acoustic pressure and three channels associated with a triaxial accelerometer from which acoustic particle velocity is obtained. IVAR was deployed on the seafloor during the Seabed Characterization Experiment (SBCEX), conducted 95 km south of Martha's Vineyard, MA, USA, in 2017. The primary goal of the SBCEX is to study the acoustics of fine-grained muddy sediments that are a prominent feature of the experimental area. For example, the upper most sediment layer commencing at the water–sediment interface is known to consist of fine-grained mudlike material [1] with geoacoustic properties largely unknown before the SBCEX [2].

The IVAR was deployed on the seafloor from *R/V Endeavor* during the SBCEX for two periods: 7 March 1645Z to 9 March 1415Z (45.5 h) and 17 March 2330Z to 18 March 2030Z (22 h). During both deployments, the IVAR recorded signals (frequency range 50–500 Hz) from a towed source (J-15) deployed from *R/V Endeavor*, the noise field from large cargo vessels operating nearby, and signals from the various experimental sound sources used by other investigators during the SBCEX.

During the second deployment, the IVAR recorded arrivals from broadband SUS (Mk-64) charges deployed from *R/V Neil Armstrong*. The focus of this study is on the IVAR observations of SUS deployments at ranges 5–13 km from the fixed IVAR location. At these ranges and in view of the ~74-m depth, there is sufficient geometric dispersion of the broadband explosive SUS pulse to allow identification of four distinct modes below 80 Hz.

This work does not engage in a geoacoustic inversion of field results *per se*; instead it presents a purely observational description of four quantities derived from the vector acoustic measurements that are sensitive to modal properties as realized at the IVAR site. These quantities are formed by the coherent combination of pressure and particle velocity and are as follows:

- 1) modal phase speed;
- 2) circularity, a measure of the normalized curl of active intensity;
- 3) depth-dependent mode speed of energy;
- 4) the vertical component of reactive intensity normalized by scalar intensity.

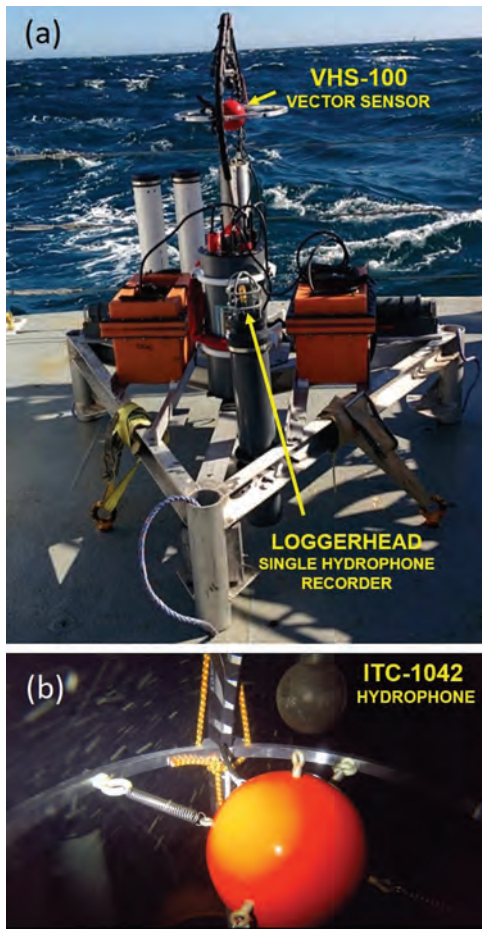


Fig. 1. Annotated photographs of IVAR (a) on aft deck of *R/V Endeavor* and (b) as deployed on seafloor. Streaks are marine snow carried by the ocean current.

To guide interpretation and provide a pathway to exploit these properties in geoacoustic inversion, a method to compute these quantities theoretically using a normal mode-based propagation code is also provided, and we present computed forms associated with a notional geoacoustic model. For example, we will demonstrate an important property of mode 2 as it goes through a transition in the neighborhood of 37 Hz; the existence of this transition and its location in frequency appears to be strongly dependent on the surficial low-speed mud layer at the IVAR site.

This paper is arranged as follows: in Section II, the IVAR system is described with key details relating to its second deployment and measurement of SUS charges. Section III describes the data processing, first covering broadband vector intensity for context, and then addressing the narrowband processing more closely associated with this study. In Section IV, the vector acoustic quantities for single-mode single frequency are formally defined along with corresponding models, and field results are presented in Section V. A summary and some additional remarks are provided in Section VI.

II. IVAR SYSTEM AND DEPLOYMENT DURING SBCEX

The IVAR system consists of a bottom-deployed tripod [see Fig. 1(a)] where key components include a three-axis accelerometer contained within a 10-cm diameter neutrally buoyant sphere

(VHS-100, Ocean Applied Acoustics) and an omnidirectional hydrophone (ITC-1042) positioned 10 cm above the center of the sphere. The accelerometer and hydrophone are coherently recorded (25 000-Hz sample rate), in four low-gain (0 dB) and four high-gain (30 dB) channels. Key metadata including water depth and sensor orientation were recorded every 15 s over the duration of the deployment. Because it was important to verify proper suspension of the neutrally buoyant sphere, a video record was taken for each deployment to document the descent phase of IVAR and first few minutes on the seafloor [see Fig. 1(b)]. Note that a second single-hydrophone recording system (Loggerhead Instruments, Inc., Sarasota, FL, USA) is also mounted on the IVAR to provide a back-up set of hydrophone data although this data stream is not recorded coherently with accelerometer data.¹

Combining co-located and coherently measured particle velocity with pressure provides a direct measure of vector intensity. Particle velocity as measured over three axes is obtained, depending on processing application, by either time integration or frequency division of the acceleration channels. With radius $a = 5$ cm and k equal to acoustic wave number based on sound speed in water, the neutrally buoyant sphere responds sufficiently similar to an accelerating parcel of water for frequencies up to about $ka \sim 0.8$, or 3750 Hz [3], although we limit our study to frequencies less than 1000 Hz to avoid any need for vertical phase corrections between pressure and particle velocity. Measurements at higher frequencies are still possible but ultimately the integrated pressure distribution over the surface of the sphere divided by mass of water displaced will not equate to acoustic particle acceleration for an equivalent volume of water.

At low frequencies, all channels are limited by the highpass filtering (-3 dB corner frequency equal to 25 Hz).² Owing to the roll-off in particle acceleration with frequency, reliable particle velocity estimates at 25 Hz require signal levels greater than about 120 dB re $1 \mu\text{Pa}$, whereas the pressure channel could detect somewhat lower levels.

For the second deployment, the IVAR was placed at location 49.48655°N , -70.63831°W where mean water depth was 74.4 m varying by ± 0.4 m owing to the M2 tidal variation [see Fig. 2(a)]. A CTD cast taken from *R/V Endeavor* [see Fig. 2(b)] shortly before recovery of IVAR shows a relatively well-mixed water column typical of other observations made during SBCEX [4]. In our subsequent manipulation of vector acoustic data, we implement the depth average as representing an isovelocity water column, with sound speed $c_w = 1468.3$ m/s.

The broadband source was the Mk-64 SUS charge consisting of 31 g of tetryl designed to detonate at notional depth of 18.3 m. These sources were deployed from *R/V Neil Armstrong* at locations (SUS stations) planned and coordinated by P. Wilson and D. Knobles and a separate study related to these sources is in preparation. At each station, a sequence of five SUS charges

¹ Some researchers in SBCEX are utilizing this hydrophone data for purposes of geoacoustic inversion.

² In hindsight, this was an overly conservative setting meant to protect the channels from possible saturation from very nearby sources. For future studies, we have set a lower corner frequency to 8 Hz.

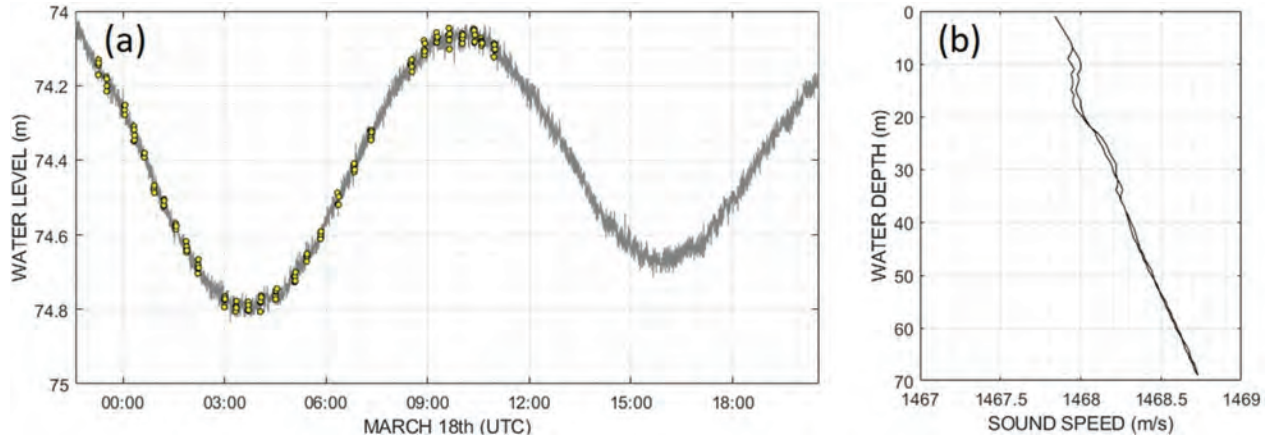


Fig. 2. (a) Water level measured by a depth sensor on the IVAR tripod, time of SUS charges indicated by circles. (b) Sound speed versus depth made by conductivity-temperature-depth (CTD) cast from *R/V Endeavor*; average speed equals 1468.3 m/s.

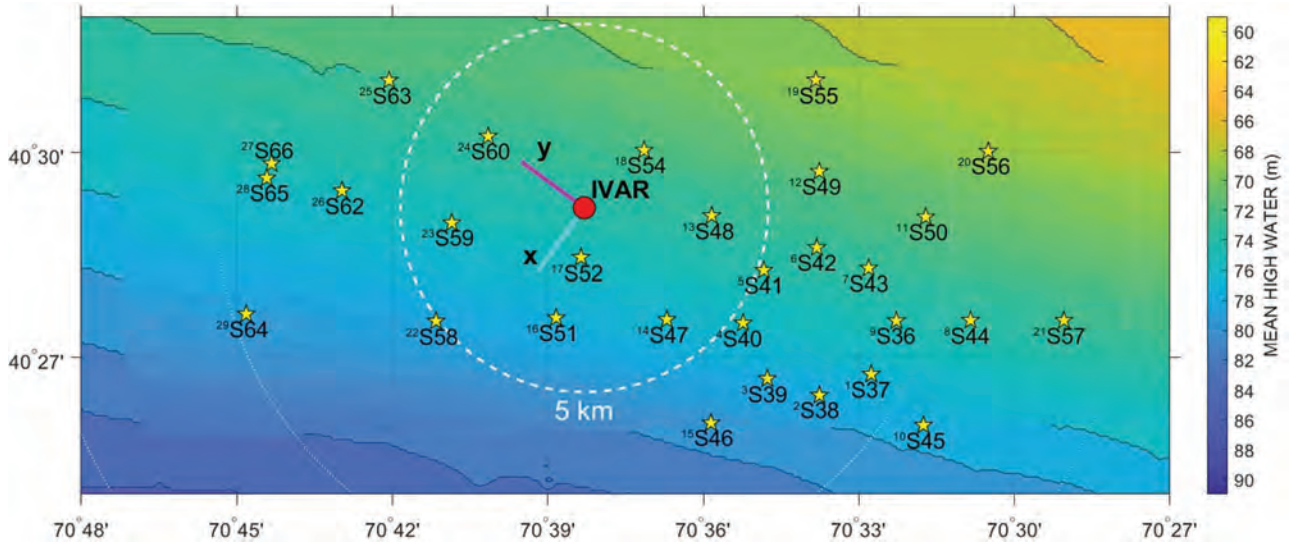


Fig. 3. Distribution of Mk-64 SUS detonation stations (stars) observed by the IVAR system (red circle); orientation of x -axis (cyan) and y -axis (magenta) indicated. Analysis is based on 22 stations outside the dashed circle delineating range 5 km from the IVAR. Note that each SUS detonation station presents a unique orientation with respect to the x and y axes of the IVAR system, e.g., the response from station S40 is manifested primarily on the y -axis.

were deployed separated in time by approximately 20 s. The second deployment of the IVAR coincided with a subset of SUS deployments, a total of 29 stations for which the range between SUS detonation (*R/V Neil Armstrong*) and IVAR location on the seabed varied between 3 and 13 km (see Fig. 3). However, to realize sufficient geometric dispersion, we limit this analysis to the 22 stations that fall outside the dashed circle in Fig. 3. The center of the neutrally buoyant sphere on the IVAR was positioned 1.25 m above the seafloor, with the x -axis aligned with true bearing 216.3° and y -axis aligned with 306.3° . For example, the bearings to stations S40 and S45 (see Fig. 3) are aligned with the y -axis.

III. CALCULATING ACOUSTIC ENERGY DENSITY AND VECTOR INTENSITY

A. Broadband Vector Intensity

In the following, broadband pressure $P(t)$ and components of particle velocity $V_{x,y,z}(t)$, over the bandwidth 10–1000 Hz,

are discussed briefly where the latter are obtained by time integration of the measured acceleration time series (although levels for frequencies less than 25 Hz are reduced somewhat owing to the aforementioned highpass filtering.) Results from a single detonation (see Fig. 4) from SUS station S40, range 5 km, shows the broadband, potential energy density $(1/2)|P(t)|^2/(\rho c_w^2)$ and kinetic energy density $(1/2)\rho|V(t)|^2$, as each varies over time. These are based on water density, ρ equal to 1027.6 kg/m^3 , and c_w equal to 1468.3 m/s. The relative time reference is set by the arrival of the peak waterborne path, and a time average over relative time period 0–0.5 s brings the two energy densities to within 0.14 dB (the 0.5-s time averaging period encompassing 99% of the energy.)

The segment of data commencing ~ 450 ms before arrival of the peak waterborne path (relative time equal to 0) suggests the onset of a ground wave [5] associated with the emergence of mode 2 at frequency ~ 22 Hz. This frequency inferred from the pattern in Fig. 4 made clear in this decibel view, with 22 Hz being too high for the cutoff of mode 1 given the water depth. Note

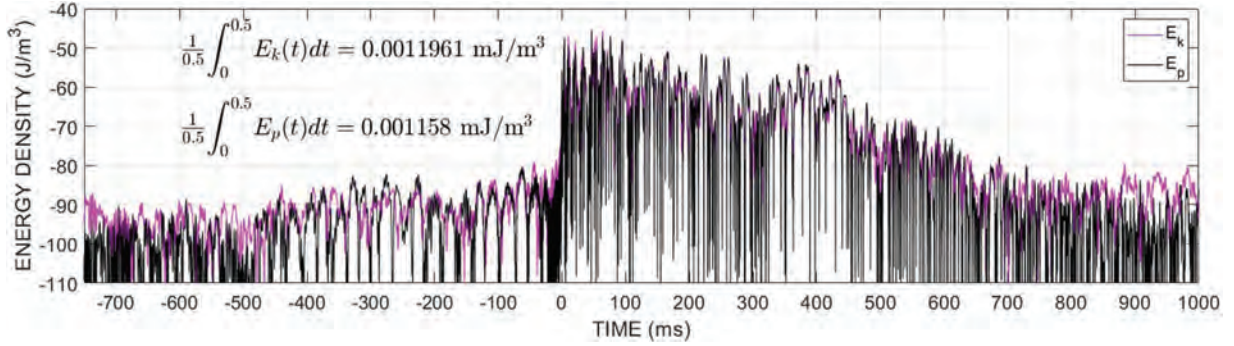


Fig. 4. Time-varying potential (black) and kinetic (magenta) energy densities measured at the IVAR site from a SUS arrival originating at station S40, range 5 km. Time is relative to the arrival of the peak waterborne path.

that the mode 2 precursor is evident in the kinetic energy density but somewhat more poorly resolved by the velocity channels because of the highpass filtering mentioned in Section II. Similarly, the relatively narrowband region (frequency ~ 28 Hz) centered about 400 ms after arrival of the peak waterborne path is likely associated with the Airy phase for mode 2; this frequency being more readily inferred from the same pattern upon expanding the scale. The received waveform embodies the expected bubble pulse [6] of period ~ 42 ms as can be confirmed with autocorrelation. The bubble pulse can produce the interference that is observed primarily at frequencies greater than about 500 Hz, at frequency intervals ~ 24 Hz. However, the bubble pulse effect is not problematic for this analysis and we make no further attempt to remove it.

Shown on a linear scale are corresponding broadband pressure (see Fig. 5, top row) and components of particle velocity (see Fig. 5, middle row), where owing to the alignment of the y-axis of the vector sensor with source direction of SUS station S40, the y-component dominates over the x-component. The Umov vector $S_{x,y,z}(t)$ or instantaneous intensity (see Fig. 5, bottom row) is formed by multiplying $P(t)$ by separate components of particle velocity.

The time average of the components of the broadband Umov vector over the same 0–0.5 s period yields estimates of the active intensity vector, with values for the separate components identified. Note that the value of the y-component of active intensity is close to an equivalent time average of $(P(t)^2 / \rho c_w)$, or scalar intensity, a result anticipated given that the y-component of particle velocity normalized by ρc_w approximately equals the pressure for this case that is the representative of a single active source with dominant energy flux in the horizontal direction. The z-component of the broadband Umov vector varies between negative and positive values; this change in direction of the sound field flow is indicative of reactive intensity [7], as defined and discussed in Section III-B. There exists a small nonzero time average in the positive z (downward) direction, and we observe the broadband vertical flux to be in general 0.03–0.04 times the corresponding horizontal flux for the 22 stations (see Fig. 3) studied.

In the remainder of this study, we examine properties associated with both active and reactive intensities in greater detail as function of mode and frequency, made possible by the geometric dispersion of the SUS arrivals for ranges greater than about

5 km. The frequency range studied will necessarily be limited to < 80 Hz, where there is sufficient time separation among modes. New notation for complex narrowband pressure and particle velocity is necessary along with model counterparts as a function of mode and frequency. We avoid reusing $P(t)$ and $V_{x,y,z}(t)$, reserving these for real broadband quantities.

B. Time–Frequency Analysis

Time–frequency analysis is done with a bank of bandpass filters applied to the original data in the time domain (using the low-gain set of channels in all cases), each with bandwidth B equal to 4 Hz centered at frequencies between 10 and 80 Hz, every 1 Hz. We use this approach rather than, say, an equivalent one involving short-time Fourier transforms, as our preference is to use intensity units over spectral densities.

An analytic signal is formed from the measured narrowband filtered time series for pressure $p_{M_i}(t)$, centered at f_i , by constructing a Hilbert-transformed pair $p_i(t) = p_{M_i}(t) + i\hat{p}_{M_i}(t)$, where $\hat{p}_{M_i}(t)$ is the Hilbert transform of the signal that is 90° out of phase with $p_{M_i}(t)$. The analytic signal $p_i(t)$ is henceforth used as a complex representation of the pressure data. Potential energy density $E_{p_i}(t)$ (J/m^3) as a function of time and centered at f_i is thus

$$E_{p_i}(t) = \frac{1}{4} |p_i(t)|^2 / (\rho c^2). \quad (1)$$

An image of $E_{p_i}(t)$ [see Fig. 6(a)] for one of the five SUS detonations at station S45 (range 10 km) shows the arrival separated into the first four modes. Results from the other four detonations from S45 are similar. We can easily identify the maximum value of $E_{p_i}(t)$ for each mode and frequency, the time–frequency locations for which are identified by the dots in Fig. 6(a). These time–frequency addresses are an important part of our analysis to identify modes as a function of frequency.

Time series for the three components of complex velocity, as in the x-component v_{x_i} centered at f_i are calculated by dividing the complex representation of the corresponding measured and narrowband filtered acceleration channel a_{x_i} by $-i2\pi f_i$, where a_{x_i} also represents a Hilbert-transformed pair. The kinetic energy density $E_{k_i}(t)$ is thus

$$E_{k_i}(t) = \frac{1}{4} \rho (|v_{x_i}(t)|^2 + |v_{y_i}(t)|^2 + |v_{z_i}(t)|^2). \quad (2)$$

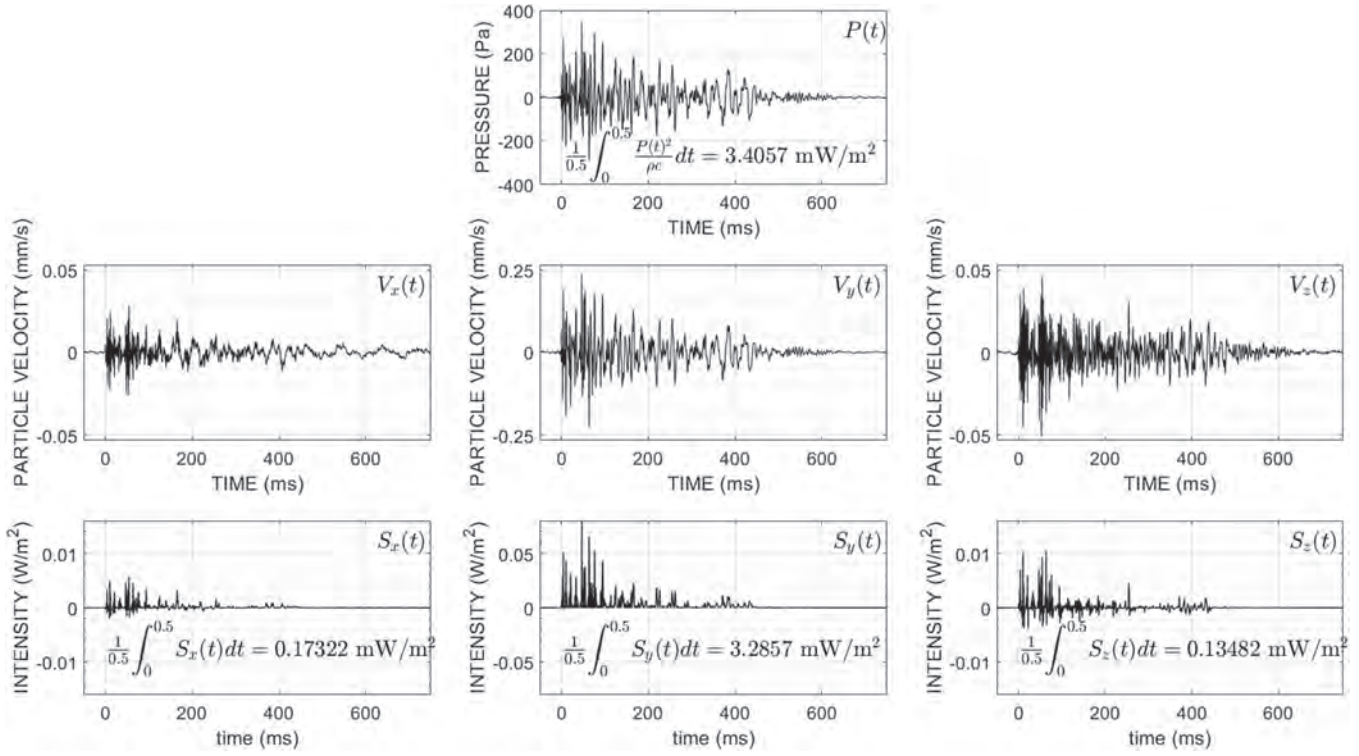


Fig. 5. Top row: Broadband pressure $P(t)$ corresponding to the data in Fig. 4, with time relative to the arrival of the peak waterborne path, also identified is the time average of squared pressure divided by ρc_w . Middle row: Components of broadband particle velocity $V_{x,y,z}(t)$ corresponding to $P(t)$. Note the y-axis for the component V_y ranges from ± 400 Pa when multiplied by ρc_w for ready comparison with $P(t)$. Bottom row: Components of the broadband Umov vector $S_{x,y,z}(t)$ and corresponding time averages.

An image of $E_{k_i}(t)$ [see Fig. 6(b)] closely mirrors $E_{p_i}(t)$, as anticipated from the broadband results (see Fig. 4).

Complex intensity $\vec{I}_c$ as formulated by Heyser [8] is computed as

$$\vec{I}_c = \frac{1}{2} p v_{x,y,z}^* \quad (3)$$

where the asterisk denotes complex conjugate. Taking the real part of $\vec{I}_c$ yields the active intensity, for which the y -component $I_{y_i}(t)$ is shown in Fig. 6(c); taking the imaginary part yields reactive intensity, where the z - or vertical-component $Q_{z_i}(t)$ is shown in Fig. 6(d) and subscript i denotes a central frequency index for these narrowband quantities. Both $I_{y_i}(t)$ and $Q_{z_i}(t)$ also separate into four modes for frequencies less than about 80 Hz. To emphasize these modal patterns, the data are only plotted where the corresponding $E_{p_i}(t)$ is within 12 dB of the maximum.

Looking ahead, we select and study values of second-order quantities including $I_{y_i}(t)$, $Q_{z_i}(t)$, and others to be defined, that are associated with the time-frequency addresses shown by the dots in Fig. 6(a). For example, a narrowband version of the Umov vector $S_{y_i}(t)$ in the y -direction at central frequency $f_i = 45$ Hz [see Fig. 6(e)] is formed by

$$S_{y_i}(t) = \text{Re}\{p_i(t)\}\text{Re}\{v_{y_i}(t)\}. \quad (4)$$

Active intensity $I_{y_i}(t)$ corresponding to a cut along 45 Hz [see Fig. 6(c), black line] finds support at modes 1, 2, and 3 [see Fig. 6(e)]. We may interpret $I_{y_i}(t)$ as a slowly varying

average value [7], [9] of $S_{y_i}(t)$. More specifically, time integrals of $S_{y_i}(t)$ and $I_{y_i}(t)$ are equal; furthermore, in this narrowband context, $S_{y_i}(t)$ can be approximately reconstructed by multiplying $I_{y_i}(t)$ by $2 \cos^2(2\pi f_i t - \phi)$ [10], where ϕ is a phase factor.

Values of $I_{y_i}(t)$ shown by the three black symbols correspond with the time-frequency addresses as extracted from $E_{p_i}(t)$. A similar cut along 30 Hz [see Fig. 6(c), red line] finds support at only modes 1 and 2 given 30 Hz is below the cutoff of mode 3; here, two values of $I_{y_i}(t)$ [see Fig. 6(e), red symbols] correspond with time-frequency addresses.

Vertical reactive intensity $Q_{z_i}(t)$ corresponding to a cut along 45 Hz [see Fig. 6(d), black line] also finds support at modes 1, 2, and 3 [see Fig. 6(f)]. In this case, the vertical component of the Umov vector $S_{z_i}(t)$ time averages to nearly or exactly zero and $Q_{z_i}(t)$ traces the envelope, with $S_{z_i}(t)$ approximately reconstructed by multiplying $Q_{z_i}(t)$ by $\sin(4\pi f_i t - \phi)$ [10]. We observe that for 45 Hz, the envelope $Q_{z_i}(t)$ at the selected values identified by black symbols is negative for modes 1 and 2 and then goes positive for mode 3. (Note: it is the *change* in sign of $Q_{z_i}(t)$ that is important, without physical significance placed on sign [11] other than it be consistent with our time convention of $e^{-i\omega t}$.) A cut along 30 Hz [see Fig. 6(d), red line] finds support at only modes 1 and 2, with the envelope $Q_{z_i}(t)$ shown in Fig. 6(f) along with two selected values identified by the red symbols. In this case, envelope $Q_{z_i}(t)$ for mode 2 is positive. The change in the sign of $Q_{z_i}(t)$ for mode 2 near ~ 37 Hz is a significant feature of the modal structure as measured at the IVAR location.

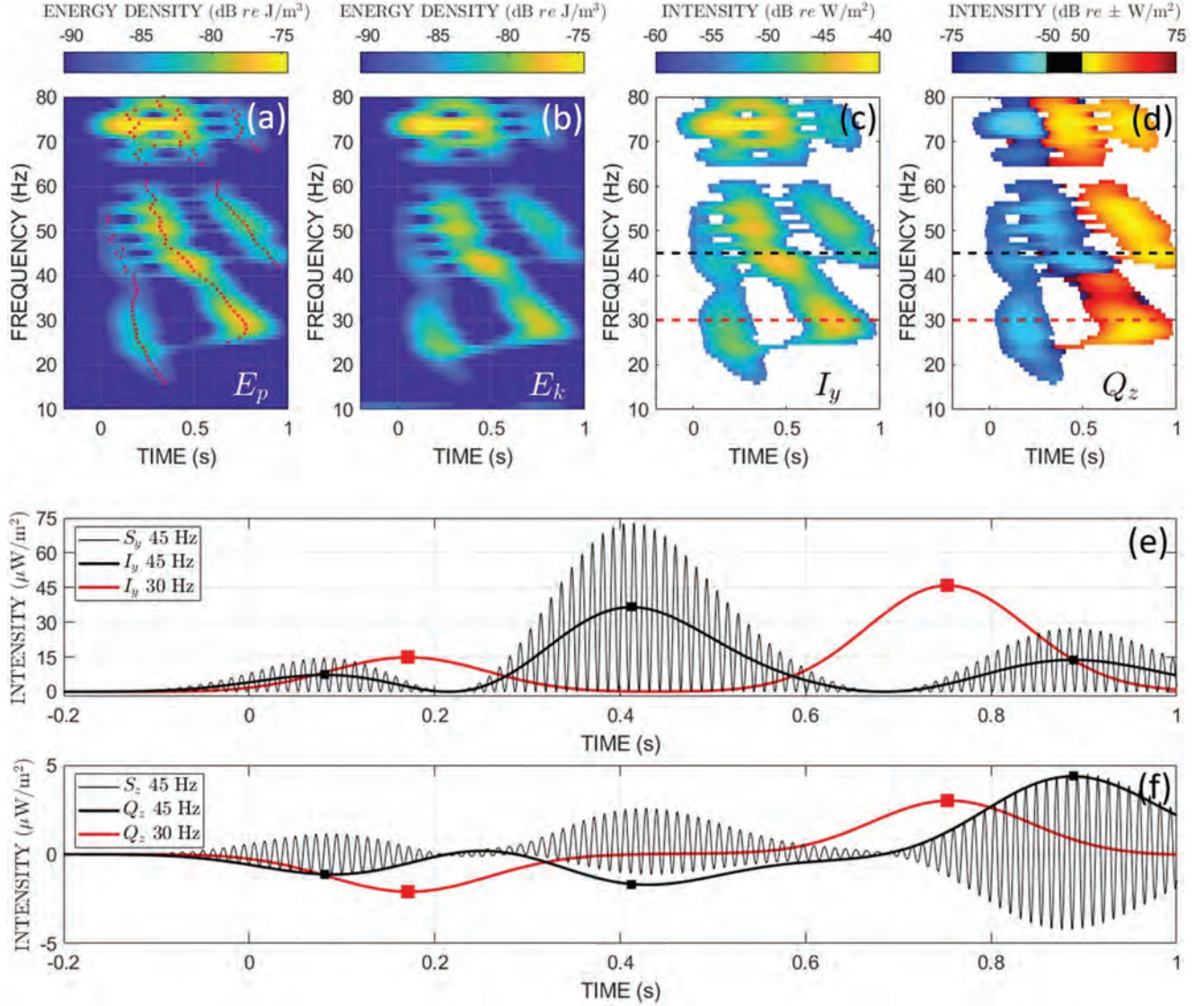


Fig. 6. (a) $E_{p_i}(t)$ measured for one of the five SUS detonations from station S45 (range 10 km). Dots corresponding to maximum values of $E_{p_i}(t)$ identify time–frequency addresses for each mode. (b) Corresponding $E_{k_i}(t)$. (c) and (d) Corresponding $I_{y_i}(t)$ and $Q_{z_i}(t)$ for which thresholding is applied; dashed horizontal lines denote cuts at central frequencies 30 and 45 Hz. (e) Cuts of $I_{y_i}(t)$ along central frequencies 30 Hz (red) and 45 Hz (black) with $S_{y_i}(t)$ centered at 45 Hz also shown for reference. Red and black symbols identify values selected from $I_{y_i}(t)$ to be used in subsequent calculations. (f) Cuts of $Q_{z_i}(t)$ along central frequencies 30 Hz (red) and 45 Hz (black) with $S_{z_i}(t)$ centered at 45 Hz also shown for reference. Red and black symbols identify values selected from $Q_{z_i}(t)$ to be used in subsequent calculations.

IV. FOUR QUANTITIES DERIVED FROM VECTOR ACOUSTIC MEASUREMENTS FOR SINGLE-MODE SINGLE-FREQUENCY AND CORRESPONDING MODELS

The intensity and energy quantities at the individual mode arrivals obtained from the approach outlined in Section III can be combined into four range-independent quantities: phase speed, depth-dependent modal speed of energy, circularity, and normalized vertical reactive intensity. These quantities are sensitive to the geoaoustic properties at the sensor location, and field data from IVAR yield estimates for modes 1–4 and frequencies between about 15 and 80 Hz (with some gaps due to multimode interference near cutoff frequencies). For each quantity, we describe means to obtain a theoretical model developed from a vertical mode function and corresponding horizontal wave

number $k_n(f)$. Any normal mode-based propagation code can be used to obtain these quantities; in our case, we use the Kraken [12] normal mode program (with quantities conjugated as necessary to align with our time convention of $e^{-i\omega t}$).

A. Phase Speed $v_{p_n}(f)$

The phase speed for mode n at frequency f is $v_{p_n}(f)$ and we adapt (27) from Mann *et al.* [10] to estimate $v_{p_n}(f)$ at discrete frequencies f_i from the data as follows:

$$v_{p_n}(f_i) = \frac{2c_w^2 E_{p_i}(t_n)}{|I|}. \quad (5)$$

Here, $E_{p_i}(t_n)$ denotes a value selected from $E_{p_i}(t)$ at the time–frequency address [see Fig. 6(a)] corresponding with mode n and frequency f_i , and similarly $|I| =$

$\sqrt{I_{x_i}^2(t_n) + I_{y_i}^2(t_n) + I_{z_i}^2(t_n)}$. For example, Fig. 6(e) (red symbols) identifies the selected values of $I_{y_i}(t_n)$ for the first two modes $n = 1, 2$ at $f_i = 30$ Hz. We adapt this notation for other metrics to be defined subsequently as in the corresponding values of $Q_{z_i}(t_n)$ [see Fig. 6(f)].

A model for phase speed is always available from a normal mode-based propagation code. Note the modal phase speed remains a local quantity, relating to the conditions that gave rise to the local mode properties, as distinct from the modal group speed that is a range-integrated quantity [13].

B. Depth-Dependent Mode Speed of Energy $u_{e_n}(z, f)$

D'Spain *et al.* [14] define a velocity of acoustic energy density transport as the ratio of active horizontal intensity to total energy, each expressed as a function of frequency, with the interpretation of this spectral ratio being the speed of net transport of acoustic energy density at the point in space where the measurement is made. The ratio is bounded by the sound speed in the medium c_w . For example, D'Spain *et al.* [14] show that the speed of energy associated with a diffuse background sound field is only about 10%–50% of the medium's sound speed, whereas this speed, when associated with more spatially concentrated sound sources, approaches c_w . This property thus relates to the relative balance between active (concentrated) and reactive (diffuse) fields, with a completely active field reaching a speed c_w and reactive field having a speed equal to 0 [15].

The variable $u_{e_n}(z, f)$ is closely analogous to this definition with the distinction that $u_{e_n}(z, f)$ is designated for individual modes n , and the point in space need only be a function of measurement depth z_m , i.e., the value of $u_{e_n}(z, f)$ does not depend on measurement range. We estimate depth-dependent mode speed of energy from the data using

$$u_{e_n}(z_m, f_i) = \frac{|I_r|}{E_{p_i}(t_n) + E_{k_i}(t_n)} \quad (6)$$

where $|I_r|$ is the magnitude of active intensity in the horizontal direction and equal to $\sqrt{I_{x_i}^2(t_n) + I_{y_i}^2(t_n)}$.

A model for $u_{e_n}(z, f)$ follows from a few variables generated by a mode-based propagation code using local geoacoustic properties and water depth at the measurement site. We start by representing the complex pressure P_n associated with the n th normal mode at range R and receiver depth z as

$$P_n = \frac{e^{ik_n R - i\frac{\pi}{4}}}{\sqrt{k_n R}} U_n(z_s, f) U_n(z, f) \quad (7)$$

where $U_n(z, f)$ is a vertical mode function, z_s is the source depth, and an asymptotic representation for the Hankel function $H_0(k_n R)$ is used. Note that everything to the left of $U_n(z, f)$ in (7) can be represented by a complex constant, call it A_n . Continuing with the single-mode single-frequency representation, the corresponding horizontal particle velocity V_{r_n} is

$$V_{r_n} = A_n k_n U_n(z, f) / (2\pi f \rho) \quad (8)$$

where a second term in V_{r_n} associated with the horizontal derivative becomes negligible compared with the first term for

ranges greater than a few wavelengths and is thus ignored here. The corresponding vertical particle velocity V_{z_n} is

$$V_{z_n} = A_n i \frac{dU_n(z, f)}{dz} / (2\pi f \rho). \quad (9)$$

Henceforth, let the abbreviations P_n , V_{r_n} , and V_{z_n} stand for complex pressure, horizontal velocity, and vertical particle velocity, respectively, for mode n , with each being a function of depth and frequency.

The model for depth-dependent mode speed of energy is thus

$$u_{e_n}(z, f) = \frac{\text{Re}\{P_n V_{r_n}^*\}}{0.5|P_n|^2 / (\rho c_w^2) + 0.5\rho(|V_{r_n}|^2 + |V_{z_n}|^2)} \quad (10)$$

where the numerator is represented by single-mode depth-dependent horizontal flux and the denominator is composed of single-mode depth-dependent potential and kinetic energy densities.³

We remark that the single-mode vertical flux $\text{Re}\{P_n V_{z_n}^*\}$ equals 0, though for simultaneous arrivals of two or more modes at the same frequency, there can be nonzero vertical flux. This interesting effect is under study but is beyond the scope of this paper. Furthermore, in evaluating the model associated with a single mode, the factor A_n is common to both the numerator and denominator and thus cancels. Therefore, the range R along with cylindrical spreading does not enter into the model result. The three models to be defined below also share this property.

It is tempting to interpret $u_{e_n}(z, f)$ as a modal group speed. However, if we evaluate the quantities in (10) for all depths and take the depth integrals of the numerator and denominator separately, we arrive precisely at the group speed for mode n and frequency f as shown by Tolstoy [16]. In that work, $2E_k$ is used instead of $E_p + E_k$, which is a statement of Rayleigh's principle [17], where integrals over the depth of the kinetic and potential energy densities are equal. Nonetheless, given our measurements are at a single depth, we show that $u_{e_n}(z, f)$ differs greatly from a modal group speed even though it displays a high degree of sensitivity to changes in geoacoustic parameters.

C. Circularity $\theta_n(z, f)$

The phase and amplitude difference in orthogonal components of the particle velocity determines the trajectory of particle motion. For example, if at some position in the field, narrowband horizontal and vertical particle velocities are of equal amplitude and 90° out of phase, the result is a perfectly circular trajectory. The other extreme is when particle velocity exists as a single component, as in single plane wave, producing a trajectory along a line. In between these two extremes, the trajectory can be elliptical [18].

The trajectory pattern is described by the variable circularity θ , which ranges from ± 1 (circular, with sign defining rotational direction) to 0 (trajectory along a line). In general, circularity is a vector with x , y , and z components describing the trajectory of particle motion projected onto the $y - z$, $x - z$, and

³Factors of 1/2 in (1) and (2) are absent here as these manipulations do not involve a Hilbert transform.

$x - y$ planes, respectively, computed using the normalized vector product of complex-valued particle velocity $\vec{v}$ [19], as in

$$\vec{\theta} = \frac{\text{Im}\{\vec{v} \times \vec{v}^*\}}{|\vec{v}|}. \quad (11)$$

Circularity may also be interpreted as the normalized curl of active intensity [20].

For many geometries describing an underwater waveguide, it is both practical and realistic to discuss circularity as a scalar metric with horizontal and vertical particle velocities establishing particle trajectory in the range–depth ($r - z$) plane. For example, such a trajectory is readily observed with a vector sensor lowered through an acoustic field simulating a Lloyd's mirror condition [22]. Measurements of scalar circularity θ as it evolves with a varying source depth that produced a change in multipath interference structure have also been used in geoacoustic inversion [19].

In this paper, we use scalar circularity defined as a function of mode number, measurement depth, and frequency, calling it $\theta_n(z, f)$. However, for our field observations, it is first necessary to project the measurements of $v_{x_i}(t)$ and $v_{y_i}(t)$ (each being complex) into a single horizontal particle velocity v_{r_i} using

$$v_{r_i} = v_{x_i} \cos(\phi_B - \phi_x) + v_{y_i} \cos(\phi_B - \phi_y) \quad (12)$$

where ϕ_x is the bearing of x channel, ϕ_y is the bearing of y channel, and ϕ_B is the bearing of IVAR from a particular SUS station. Knowing $v_{r_i}(t)$ and $v_{z_i}(t)$, the equation to estimate scalar circularity from field data reduces to

$$\theta_n(z_m, f_i) = \frac{2 \text{Im}\{v_{r_i}(t_n) v_{z_i}^*(t_n)\}}{|v_{r_i}(t_n)|^2 + |v_{z_i}(t_n)|^2}. \quad (13)$$

A model for $\theta_n(z, f)$ emerges by using previously derived model values for V_{r_n} and V_{z_n} as follows:

$$\theta_n(z, f) = \frac{2 \text{Im}\{V_{r_n} V_{z_n}^*\}}{|V_{r_n}|^2 + |V_{z_n}|^2}. \quad (14)$$

D. Normalized Vertical Reactive Intensity $Q_{z_n}^*(z, f)$

The vertical component of reactive intensity was introduced [see Fig. 6(d)]. D'Spain *et al.* [14] explain the significance of vector quantity $\vec{Q}$ by multiplying the equation for conservation of momentum by pressure and then operating in the spectral domain. It is useful to provide here a small variation on this development; keeping in the time domain and using the Hilbert transformed variables (see Section III) yields

$$i2\pi f \rho p \vec{v}^* + p \nabla p^* = 0. \quad (15)$$

Assuming a spatial dependence in p going as $|p(x, y, z)| e^{i\phi(x, y, z)}$ gives

$$\pi f \rho \vec{Q} + i\pi f \rho \vec{I} + |p| \nabla |p| + i|p|^2 \nabla \phi = 0 \quad (16)$$

and after equating real and imaginary parts and dividing by $|p|^2$, we obtain the desired result as

$$\rho c_w \frac{\vec{Q}}{|p|^2} = \frac{\nabla |p|^2 \lambda}{4\pi |p|^2} \quad (17)$$

with the interpretation that reactive intensity normalized by a scalar intensity gives the fractional change of field magnitude squared per unit wavelength [14].

Normalizing reactive intensity $\vec{Q}$ by a scalar intensity ($|p|^2 / \rho c_w$) removes the range dependence and provides advantages because important properties emerge in regions of low signal level (see the research work by Dall'Osto *et al.* [21]). We refer to this normalized quantity as $\vec{Q}^*$ (where the star symbol identifies this as a normalized quantity and should not be confused with the complex conjugation.) The immediate focus in this paper is on the vertical component of $\vec{Q}^*$, which, as in the above metrics, is defined here as the function of mode number, measurement depth, and frequency, or $Q_{z_n}^*(z, f)$. From field data, we estimate $Q_{z_n}^*(z, f)$ as

$$Q_{z_n}^*(z_m, f_i) = \rho c_w \frac{Q_{z_i}(t_n)}{|p_i(t_n)|^2} \quad (18)$$

and a model for $Q_{z_n}^*(z, f)$ using the previously derived single-mode pressure and particle velocity as a function of frequency is

$$Q_{z_n}^*(z, f) = \rho c_w \frac{\text{Im}\{P_n V_{z_n}^*\}}{|P_n|^2}. \quad (19)$$

Note the behavior of $Q_{z_n}^*(z_m, f_i)$ and $\theta_n(z_m, f_i)$ and corresponding models will be similar, as anticipated from the numerators of (14) and (19), both of which govern the sign change. That is, given that the radial particle velocity $v_{r_i}(t)$ and pressure $p_i(t)$ are likely to be nearly exactly in phase for the active field then $Q_{z_n}^*(z_m, f_i)$, which is based on the latter, will have similar behavior. However, each provides an independent examination of the data, because the denominator of $\theta_n(z_m, f_i)$ includes both horizontal and vertical components of particle velocity and this quantity is bound by ± 1 , whereas that of $Q_{z_n}^*(z_m, f_i)$ is based on pressure and can assume extreme values, especially when evaluated near complicated multimode interference structures [21].

E. Comparison of Model Results Based on Two Geoacoustic Models

Model results for the four quantities derived from the vector acoustic measurements are compared using two different geoacoustic representations (or geoacoustic models), the first being a notional one for the SBCEX experimental conditions corresponding to the IVAR location and the second being a half-space, or Pekeris representation (see Table I). We emphasize that the notional geoacoustic model is not a result of an inversion *per se* but instead meant as a nominally consistent representation of available ground truth data in terms of water depth measured at IVAR (mean depth, 74.4 m), measured water sound speed c_w , and approximate mud-layer thickness at the IVAR site based high-resolution chirp acoustic reflection data [1]. Some experimentation with forward modeling is required to establish parameters for the mud layer, a key component of the notional geoacoustic model, and we use values consistent with those emerging from recently published studies [2], [4], such as mud-layer thickness and linear sound-speed gradient equal to 10 s^{-1} .

TABLE I
SUMMARY OF GEOACOUSTIC REPRESENTATIONS

Notional SBCEX	Layer Thickness	Sound Speed	Density	Attenuation
Water	74.4 m	1468.3 m/s	1027 kg/m ³	0 dB/λ
Mud	11 m	1445-1555 m/s	1600 kg/m ³	0.05 dB/λ
Halfspace	semi-infinite	1830 m/s	2000 kg/m ³	0.25 dB/λ
Pekeris	Layer Thickness	Sound Speed	Density	Attenuation
Water	74.4 m	1468.3 m/s	1027 kg/m ³	0 dB/λ
Halfspace	semi-infinite	1830 m/s	2000 kg/m ³	0.25 dB/λ

We first undertake a brief analysis of sediment attenuation to confirm that the attenuation parameters (see Table I) are at least nominally consistent with the data. For a given source station, active horizontal intensity for modes $n = 1, 2, 3$ and frequency indices f_i between about 15 and 60 Hz (depending on mode) is taken to be $\sqrt{I_{x_i}^2(t_n) + I_{y_i}^2(t_n)}$. For example, for the SUS station S45 at range 10 km [see Fig. 6(e)], active horizontal intensity is dominated by the y -component and $I_{y_i}(t_n)$ at 30 Hz for modes 1 and 2 are 0.05 and 0.13 mW/m², respectively.

Data from all stations studied (see Fig. 3) are collected in this manner, and we assume these data take on a range behavior embodied by $|A_n|^2$, which will have the range dependence going as $e^{-2\text{Im}\{k_n\}R}/R$. The cylindrical spreading term is removed, and what remains is the decay for a particular mode governed by the imaginary part of the modal horizontal wave number $k_n(f_i)$. For example, the entire set of active horizontal intensity data for mode 2, 30 Hz (see Fig. 7 inset) is fitted to a single curve, with cylindrical spreading built in, and an estimate of $\text{Im}\{k_n(f_i)\}$ is then derived from this curve fit (solid line in Fig. 7 inset). Results for the first three modes (see Fig. 7) show that the imaginary part of the horizontal wave number increases rapidly near the cutoff of the mode, and then assumes a more constant value. Admittedly, this is a delicate operation on the data with results susceptible to interference effects. Nonetheless, the analysis confirms that $\text{Im}\{k_n\}$ values derived from the notional SBCEX geoacoustic model based on less attenuation in the mud layer than in the sediment half-space (see Fig. 7, solid, black lines) are reasonably consistent.

More detail is required to describe sediment attenuation properly. For now, we accept this deficiency in our notional SBCEX geoacoustic model given its purpose in this paper, with the results (see Fig. 7) motivating a more refined inversion on sediment attenuation. Finally, we note that this analysis can also be undertaken using potential energy $E_{p_i}(t_n)$ measured as a function of range based on a single pressure sensor (thick, dotted lines in Fig. 7). These results are in agreement with those derived from active horizontal intensity with the exception of mode 1, which covers a much lower frequency range. Here signal-to-noise limitations that affect the pressure and velocity channels differently can be an issue.

Based on the geoacoustic data in Table I, we compute, as a function of frequency for modes 1–4, model results (see Fig. 8) for depth-dependent mode speed of energy $u_{e_n}(z, f)$ (10), circularity $\theta_n(z, f)$ (14), and normalized vertical reactive intensity $Q_{z_n}^*(z, f)$ (19). Also coming directly from the normal mode calculations are phase speed $v_{p_n}(f)$ and group speed $v_{g_n}(f)$, for which the latter, although not included in the four quantities to be derived from the vector acoustic measurements, will be interesting to include.

The different behaviors for $u_{e_n}(z, f)$, $\theta_n(z, f)$, and $Q_{z_n}^*(z, f)$ based on notional SBCEX and Pekeris models are striking, and suggests that these quantities, when in the form of reliable field data, have great potential to resolve information about the seabed. When based on the notional SBCEX model, both $\theta_n(z, f)$ and $Q_{z_n}^*(z, f)$ also undergo a change in sign for mode 2 at 37 Hz, whereas when based on the Pekeris model, the sign change for mode 2 occurs very close to, if not precisely at, the cutoff frequency for mode 2, which is approximately 25 Hz. In terms of the parameters given in Table I, the mud-layer thickness combined with the average compressional wave speed within this layer appears to have the greatest controlling influence on this property.

V. RESULTS

Experimental values (see Fig. 9) are presented for the mode- and frequency-dependent vector acoustic quantities (see Sections IV-A–IV-D), based on observations from 22 SUS stations (see Fig. 3) for which the range to IVAR exceeds 5 km and there is sufficient dispersion to identify separate mode arrivals (see Fig. 6(a)). Additionally, the modal group speed $v_{g_n}(f_i)$ is estimated directly from the time–frequency address locations generated from E_p for any arrival [see Fig. 6(a)]. Given the known range R between SUS detonation and IVAR and water sound speed c_w , $v_{g_n}(f_i) = R/t$, where $t = t_0 + \Delta t$ is the total travel time, with Δt established by the time–frequency address and $t_0 = R/c_w$ is the arrival time of the broadband peak.

Each quantity has 110 independent estimates, based on the five SUS detonations for a given station (range) and 22 stations used in this analysis. As a measure of central tendency and to avoid undue influence of outliers, we use the median value

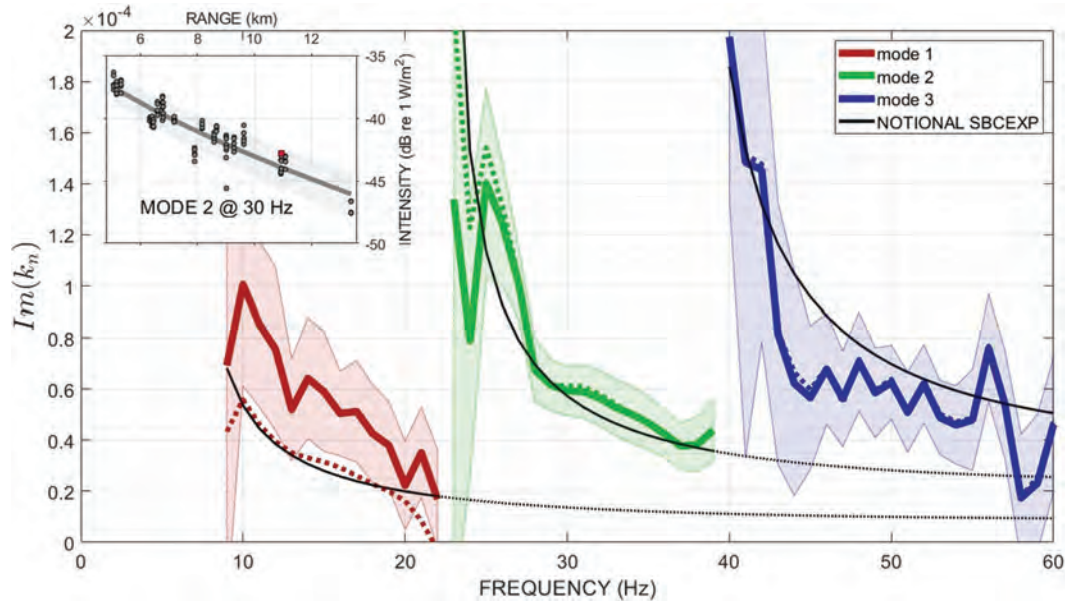


Fig. 7. Imaginary part of horizontal wave number k_n for modes $n = 1, 2, 3$ as derived from analysis of horizontal intensity from SUS arrivals measured at the IVAR site, ranges 5–13 km. Thicker color-coded solid lines represent the median estimate of $\text{Im}\{k_n\}$ as a function of central frequency f_i , with shading bracketing the 95th percentile range. Color-coded dotted lines are equivalent estimates based on potential energy (see text) that align with those based on horizontal intensity with exception of mode 1. Solid, black lines are values $\text{Im}\{k_n\}$ from the Kraken normal mode program upon using the attenuation values in Table I. Inset: Example of active horizontal intensity as function of range for mode 2 and central frequency 30 Hz. Thick line is fitted curve from which estimates of $\text{Im}\{k_n\}$ are derived.

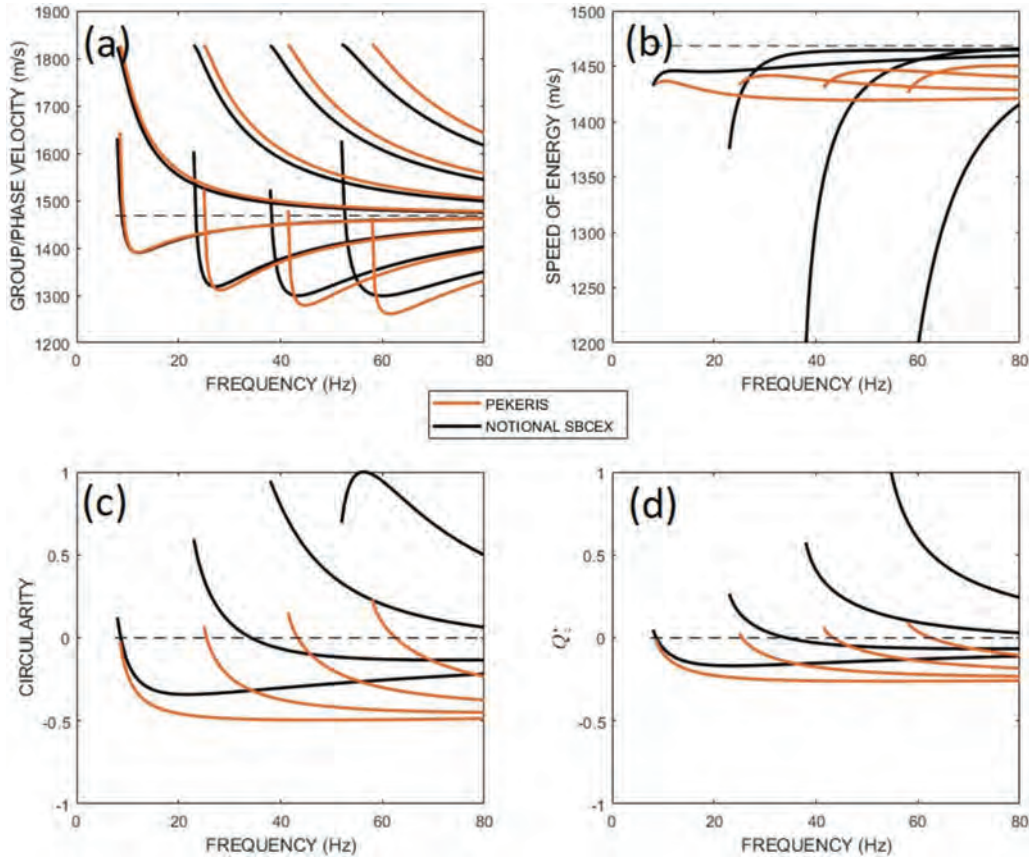


Fig. 8. Theoretical predictions for the four vector acoustic quantities plus group speed, based on the two geoacoustic models in Table I. (a) Phase speed $v_{pn}(f)$ (above the horizontal dashed line c_w) and corresponding group speed $v_{gn}(f)$. (b)–(d) Depth-dependent vector acoustic quantities evaluated at IVAR depth: (b) mode speed of energy $u_{en}(z, f)$ with horizontal dashed line equal to c_w , (c) scalar circularity $\theta_n(z, f)$, and (d) vertical component of reactive intensity normalized by scalar intensity $Q_{zn}^+(z, f)$

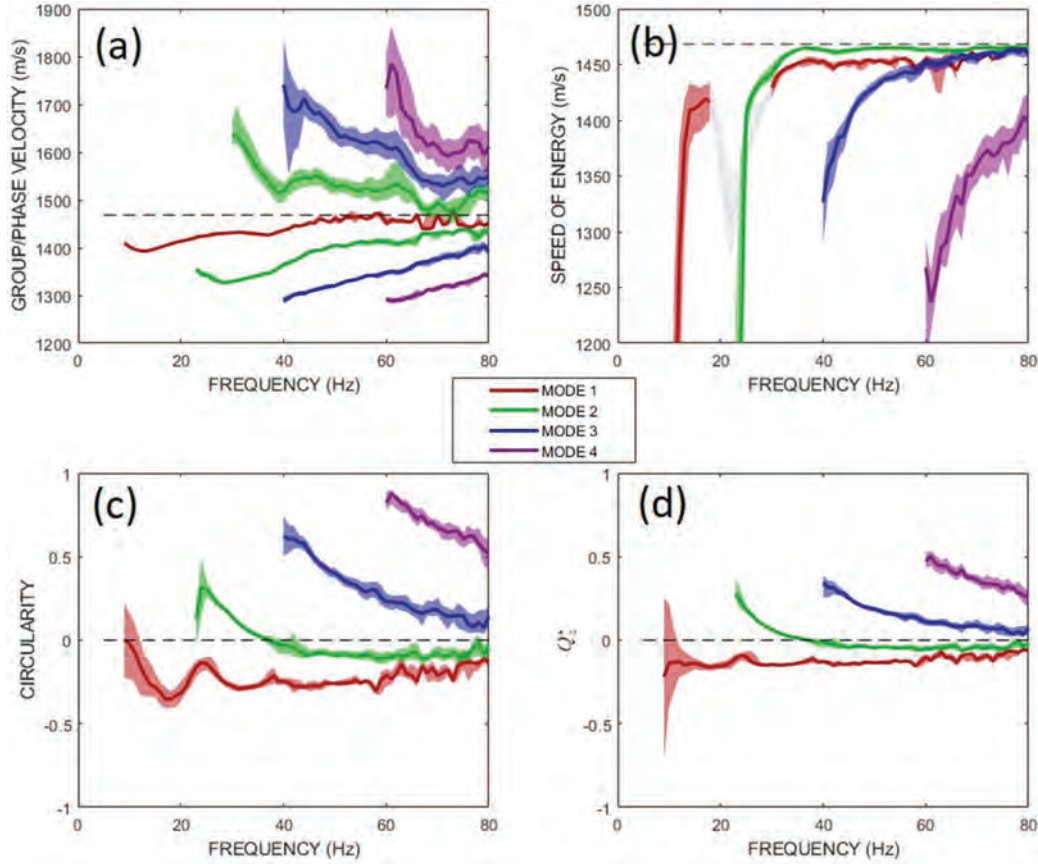


Fig. 9. (a) Experimental values of phase speed $v_{pn}(f_i)$ (above the horizontal dashed line) and group speed $v_{gn}(f_i)$ (below the dashed line). (b) Mode speed of energy $u_{en}(z_m, f_i)$. (c) Scalar circularity $\theta_n(z_m, f_i)$. (d) Vertical component of reactive intensity normalized by scalar intensity $Q_{zn}^*(z_m, f_i)$.

as the final estimate (thick lines in Fig. 9) with uncertainty characterized by the 25th (lower bound) and 75th percentiles.

Group speed estimates based on the pressure channel [see Fig. 9(a)] suggest a frequency of the Airy phase for mode 2 at 28 Hz, which is in agreement with that recently reported by Wan *et al.* [4]; additionally, we report an Airy phase group speed for mode 2 equal to 1328 m/s (median), with a 25th–75th percentile range of 1326–1333 m/s. However, signal-to-noise limitations prevented estimates of the Airy phase for modes 3 and 4. The Airy phase of mode 1 has a frequency of 13 Hz and speed 1393 m/s with 25th–75th percentile equal to 1392–1396 m/s. The estimates of group speed are from varying angular sectors (see Fig. 3) and thus necessarily represent a range average over differing mud thicknesses [1], see also [4, Fig. 1], yet the bounds on these estimates are reasonably tight. This observation is anticipated based on the results from the notional geoacoustic model [see Fig. 8(a)], for which group velocities (black lines) are consistent with our experimental values for mode 1 and mode 2; however, these results are expected to shift little by changing the mud-layer thickness a meter or two because the Pekeris model yields similar results.

For estimates of phase speed $v_{pn}(f)$ [estimates located above the dashed line equal to c_w in Fig. 9(a)], variation about the median for any given frequency is greater and a reliable estimate of mode 1 phase speed is not possible, although the phase speed estimates obtained are reasonably comparable with those from

the notional geoacoustic model [see Fig. 8(a)]. As with group speed, model estimates of phase speed also show considerable similarity between the two widely different geoacoustic models, particularly for modes 1 and 2, and we anticipate that these observations offer a lower measure of information about the seabed.

The three quantities relating to individual-mode frequency-dependent estimates of the mode speed of energy [see Fig. 9(b)], circularity [see Fig. 9(c)], and normalized vertical reactive intensity [see Fig. 9(d)], all of which are depth dependent, present an interesting collective case. Inspecting their patterns versus frequency and mode number suggests that there is information in these data that motivates resolving more than a half-space, or Pekeris, representation for a geoacoustic model, and that something like the notional geoacoustic model (see Table I) is required. At this point, we postpone a formal geoacoustic inversion to future work or to works by other researchers studying these data.

However, a key property of mode 2 as observed at the IVAR location is the zero crossing near 37 Hz for estimates of $\theta_n(z_m, f_i)$ [see Fig. 9(c)] and $Q_{zn}^*(z_m, f_i)$ [see Fig. 9(d)]; any geoacoustic model that originates from this experiment ought to exhibit this property in mode 2 when applied to the IVAR location (depth 74.4 m). Thus, we posit this value as a constraint observation for mode 2, with formal median value of 37.3 Hz and 25th–75th percentile range of 36–39 Hz.

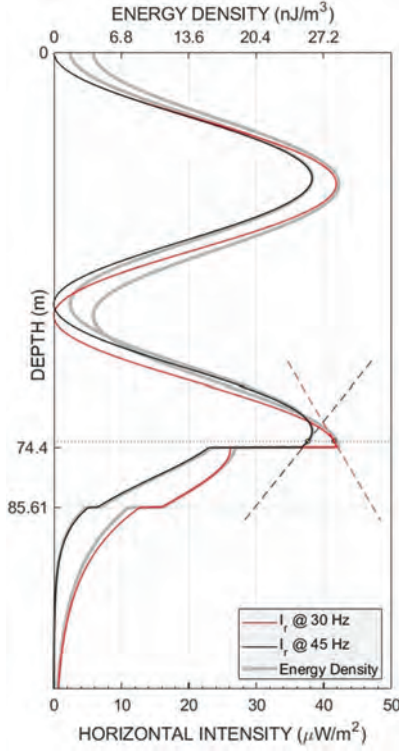


Fig. 10. Horizontal intensity for mode 2 at 30 Hz (red) and 45 Hz (black) assuming the notional SBCEX geoacoustic model (see Table I) combined with true measurements made at the IVAR measurement depth (horizontal dotted line). Energy densities (thick gray lines) follow closely the corresponding horizontal intensities as seen by the overlapping lines, which separate toward the sea surface. Two slope indicators (short, dashed lines) indicate the sign of the vertical derivative of the pressure magnitude squared at the IVAR measurement depth.

To further understand this property, we examine the behavior of mode 2 at two frequencies that span 37 Hz (see Fig. 10) based on the notional SBCEX geoacoustic model (see Table I). Take for purposes of demonstration, values for energy density $E_{p_i}(t_n) + E_{k_i}(t_n)$ and horizontal intensity $\sqrt{I_{x_i}^2(t_n) + I_{y_i}^2(t_n)}$ observed at the IVAR measurement depth z_m for mode 2 at 30 Hz and 45 Hz, as can be inferred from Fig. 6(a)–(c), noting in this case $I_{x_i}(t_n) \approx 0$. Using the notional SBCEX geoacoustic model, we compute $U_n(z)$ and k_n for $n = 2$ at 30 and 45 Hz and derive an estimate of $|A_n|^2$ for $n = 2$ at these frequencies by equating the measured to theoretical values of horizontal intensity I_r , where

$$I_r = \frac{|A_n|^2 \text{Re}\{k_n\} |U_n(z)|^2}{2\pi f \rho(z)}. \quad (20)$$

Using (20), I_r may now be extrapolated over the entire water column and sediment depth where we require a depth-dependent density $\rho(z)$. An analogous operation is applied to energy density, with both I_r and $E_p + E_k$ as functions of depth shown for mode 2 at frequencies 30 and 45 Hz (see Fig. 10).

Returning to the original issue of the zero crossing, take I_r as surrogate for $|p|^2$ as used in (17) to demonstrate how reactive intensity relates to the gradient of the pressure magnitude squared. The vertical derivative of I_r changes sign at the IVAR measurement depth between frequencies 30 and 45 Hz

(see slope indicators, Fig. 10) and equals 0 at approximately 37 Hz, which explains the behavior in $Q_{z_n}^*(z_m, f_i)$. Similarly, on a single-mode basis, pressure and horizontal particle velocity are in phase, and therefore estimates of scalar circularity behave like $Q_{z_n}^*(z_m, f_i)$ in terms of the sign change property for mode 2. (Observe that I_r can be discontinuous across the water–sediment boundary, whereas I_z will be continuous [23].)

Estimates for the modal speed of energy [see Fig. 9(b)], which assume seemingly nonintuitive values [i.e., resembling nothing like the phase or group speeds shown in Figs. 8(a) and 9(a)], mirror the estimates based on the notional SBCEX model [see Fig. 8(b)]. Over frequencies 30–45 Hz, estimates for the speed of energy for mode 2 vary smoothly from ~ 1442 m/s to ~ 1465 m/s, which is slightly less than the c_w value and there are similar changes observed for modes 1, 3, and 4 but over different frequency ranges.

VI. SUMMARY AND ADDITIONAL REMARKS

The IVAR is a system that records four coherent channels of acoustic data continuously: one channel for acoustic pressure and three channels associated with a triaxial accelerometer from which acoustic particle velocity is obtained. Using the IVAR, the vector acoustic field of broadband signals originating from SUS (Mk-64) charges deployed at ranges 5–13 km from the fixed IVAR site (mean depth 74.4 m) were studied as part of the 2017 SBCEX relating to the study of the acoustics of fine-grained muddy sediments. Sufficient geometric dispersion at these ranges permitted unambiguous identification of up to four modes as a function of frequency in the range ~ 15 –80 Hz.

From the time–frequency analysis of the dispersed arrivals, time–frequency addresses of single-mode (n) and single-frequency (f_i) arrivals are identified. Four vector acoustic quantities are estimated at each address: first, mode phase speed $v_{p_n}(f_i)$; second, depth-dependent mode speed of energy $u_{e_n}(z_m, f_i)$; third, scalar circularity $\theta_n(z_m, f_i)$; and fourth, normalized vertical reactive intensity $Q_{z_n}^*(z_m, f_i)$, for which the last three depend on the IVAR measurement depth z_m of 1.25 above the seafloor. In addition, modal group speed $v_{g_n}(f_i)$ is estimated directly from the dispersed arrivals measured on the pressure channel.

A comprehensive feature of these observations, measured at ranges 5–13 km, is the general collapse onto a single curve as a function of frequency for a given mode, although some better than others. This implies that these data represent a measure of the local mode properties as realized at the IVAR site; the observations of group speed are an exception in that they represent an average group speed for the SBCEX experimental area at the particular measurement range [2].

The observations are easily modeled using a normal mode-based propagation code providing a pathway for geoacoustic inversion. A comparison of observations with model results, with the latter based on: first, a notional geoacoustic representation for the SBCEX experimental area consisting of single low-speed mud layer over a half-space, and second, a Pekeris representation based on the same half-space (see Table I), shows striking differences (see Fig. 8). The field observations (see Fig. 9) are clearly at variance with the Pekeris representation. The notional

geoacoustic representation is designed to be consistent with available ground truth and incorporate sediment attenuation parameters based on experimental results on the range decay of identifiable mode arrivals to estimate $\text{Im}\{k_n\}$. Beyond this, a formal inversion to assess more quantitatively the resolving power of these data, for example, the ability to resolve sound-speed gradients, or additional granularity in sediment layering, requires further study.

Nonetheless, the notional geoacoustic representation for the SBCEX experimental area does provide some guidance. In particular, mode properties emerging from it predict well the zero crossing near 37 Hz for mode circularity [see Fig. 8(c)] and normalized vertical reactive intensity [see Fig. 8(d)]. This effect is manifested in observations of $\theta_n(z_m, f_i)$ and $Q_{z_n}^*(z_m, f_i)$ in the form of a zero crossing and change in sign, a property that is observed consistently in more than 100 observations based on the 5–13 km source range set. It is a fundamental feature of the mode structure as realized at the IVAR site that cannot be reproduced in the absence of a low-speed, mudlike layer.

Finally, although it is demonstrated that information content in $u_{e_n}(z_m, f_i)$, $\theta_n(z_m, f_i)$, and $Q_{z_n}^*(z_m, f_i)$ as data measures for geoacoustic inversion appears to be high, they are not sensitive to sediment attenuation. Note that this insensitivity is a feature of the single-mode representation of these quantities, and then for a field subject to multimode interference, range dependence and sensitivity to attenuation likely would be exhibited. However, our analysis of active horizontal intensity as a function of mode and frequency for all ranges to obtain estimates of $\text{Im}\{k_n\}$ suggests that much less attenuation in the mud layer than in the sediment half-space (see Table I) is required to be compatible with observations. It is possible that other vector acoustic quantities, such as active vertical intensity or reactive horizontal intensity, will be of greater use as a measure of sediment attenuation, and furthermore not require observations over range. This, too, will be assessed in future work.

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such theoretical predictions through experiment.

EFFICIENT MODELING OF 3D ACOUSTIC PATHS TO IMPROVE SOURCE TRIANGULATION

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Abstract: *Hydroacoustic signals recorded on the International Monitoring System (IMS) network have proven their capability to identify the origin of intense sound sources. A recent example is the detections CTBTO used to identify the search area where the lost Argentine submarine ARA San Juan was found. To triangulate a source, isochrones or surfaces of equal travel time are propagated from each station using a global model of ocean sound speed. With detections on two stations, the intersection of these isochrones form a line, which reduces to point when time of occurrence is known. With detections on 3 stations, isochrones intersect at the source origin and establish a time of occurrence, noting that confidence is limited by accuracy of the propagation model. Finding a detection on three stations however is not always possible, and as such azimuthal information garnered from coherent processing of the hydrophone triads that make up each IMS station provide another means to bound the triangulation. Furthermore, when additional arrivals distributed in azimuth can be associated with a particular source, e.g. delayed arrivals having a common spectral feature, these 3-dimensional paths can be modelled to establish additional isochrones. This serves as an addition of “virtual” stations to improve triangulation, and is demonstrated using the bathymetrically refracted 3D features observed in the signal of the ARA San Juan. Spectral and cepstral features allow for unambiguous association of the 3D arrivals recorded HA10-Ascension and HA04-Crozet. This study concludes with an assessment of the accuracy, limitations and efficiency of 3D modelling techniques based on hybrid of rays, acoustic modes and the parabolic equation.*

Keywords: *3D acoustics, normal modes, long-range propagation*

1. INTRODUCTION

On November 15th, 2017 an intense sonic impulse was recorded by two Comprehensive Nuclear Test Ban Treaty (CTBTO) hydroacoustic stations. This sound was generated by the catastrophic failure of *ARA San Juan* (a submarine) hull as it sank to the bottom of the ocean.[1] This intense signal propagated 6000 km to Ascension Island (HA10) and 8000 km to the Crozet Islands (HA04). The signal contains a wealth of information relating to the origin of the sound as well as oceanography.

Echoes of intense impulses produce a long duration coda, which in the case of a nuclear detonation lasts for hours.[2] The coda of the *San Juan* impulse observed at the Mid-Atlantic station was detectable for over 15 minutes, and consisted of delayed arrivals from multiple directions.[3] These 3D arrivals were sound energy redirected, i.e. refracted, by ocean topography (bathymetry).[4] This focused study develops an acoustic propagation model to reliably reproduce three-dimensional (3D) features (an example is the dotted line in Fig. 1).

This paper is organized as follows: first, a forward model reproduces characteristics of the observed signal dispersion. This forward model provides important information relating to modal arrival times needed for triangulation. Next, timing of distinct modal arrivals is modelled with adiabatic mode theory, and a piecewise approach efficiently reconstructs the energy path of 3D arrivals. The paper concludes with triangulating *San Juan* based on three arrivals (those shown in Fig. 1).

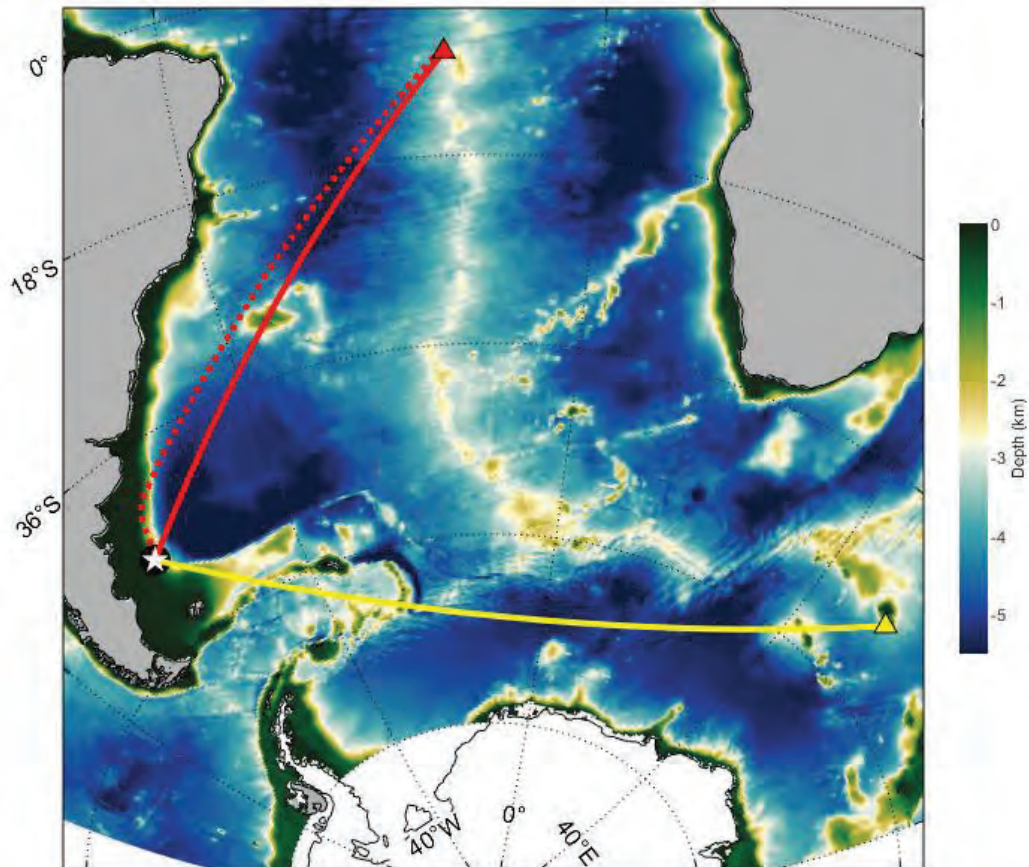


Fig. 1: Acoustics paths to H10N (red) and H04S (yellow) used for triangulation.

2. FORWARD MODELING PROPAGATION (FEATURE IDENTIFICATION)

Modelling propagation paths at megameter scale requires some careful considerations. Boundary interactions and interplay with oceanography are fundamental aspects of long-range sound propagation. This vertical confinement, or trapping of sound energy makes long range acoustic detection possible. Sound trapping by boundaries, the characteristic defining shallow water propagation, is efficient when wavefronts of the incident field propagate at a low (horizontal) grazing angle. For bottom reflections, sound is nearly perfectly reflected at grazing angles less than the critical angle, $\Theta_c = \cos^{-1}(n)$ where n is the ratio of sound speed (index of refraction) across the interface. Propagation can be approximated by a set of discrete trapped modes populating propagation angles from horizontal to Θ_c . As frequency increases so does the number of modes, and the mode-1 propagation angle migrates closer to horizontal.

In the deep ocean, very little sound energy propagates to the sea floor due to a gradient in sound speed caused by increasing pressure (roughly an increase of 10 m/s per km depth). This turning of energy is more efficient than a boundary reflection, as scattering from surface roughness is avoided. In addition to upward refraction, downward refraction by temperature gradients in the upper ocean form a true sound speed duct known as the Sound Fixing and Ranging (SOFAR) channel.[3] In avoiding scattering from the sea surface and sea floor, sound in the SOFAR channel propagates great distances.

The most basic model of a propagation path in latitude and longitude is the shortest path on the surface of the Earth. These geodesics are defined here on the World Geodetic System (WGS84). Although providing a reasonable representation of the sound energy path, prediction of the arrival time also depends on the meandering depth of the sound energy. This aspect elongates the propagation path, but as speed of sound also changes with depth, dispersion in mode arrivals is geospatially dependent. The depth dependent speed of sound (sound speed profile) along the geodesic from [45.9402° S, 59.8101° W] to the two CTBTO hydroacoustic stations are shown in Fig 2; observe the SOFAR channel at HA10 (top).

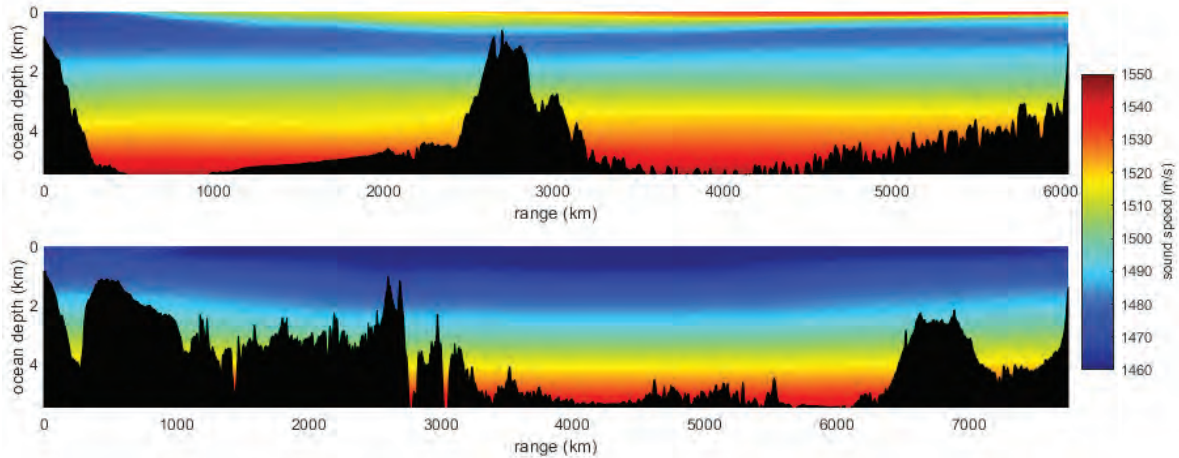


Fig. 2: Sound speed profiles along the propagation path to HA10 (top) and HA04 (bottom). Data tabulated from the World Ocean Atlas.

A two dimensional propagation model (along a geodesic and depth) provides valuable insight into the time frequency characteristics of the direct energy path. Propagation models cast in a Cartesian coordinate system must implement an Earth flattening transformation to account for path shortening in depth for a given arc length. This applies to both sound speed and ocean depth, which are multiplied by the ratio $R / (R - D)$, where R is the radius of Earth, and D is depth.

Figure 3 shows a model of the direct field at HA10 and HA04, based on the numerical PE solver RAM-PE.[5] The time series are a Fourier synthesis of 601 discrete frequencies, with time-frequency characteristics showing a dispersed signal similar to those observed in the data (see Fig. 4). A matched field comparison can provide a precise estimate of the source range (and time); however it is worth noting the computation time to produce Fig. 3 was nearly 24-hrs. Although at long ranges such numerical methods are slow, the full wave-representation maintains a high degree of accuracy.

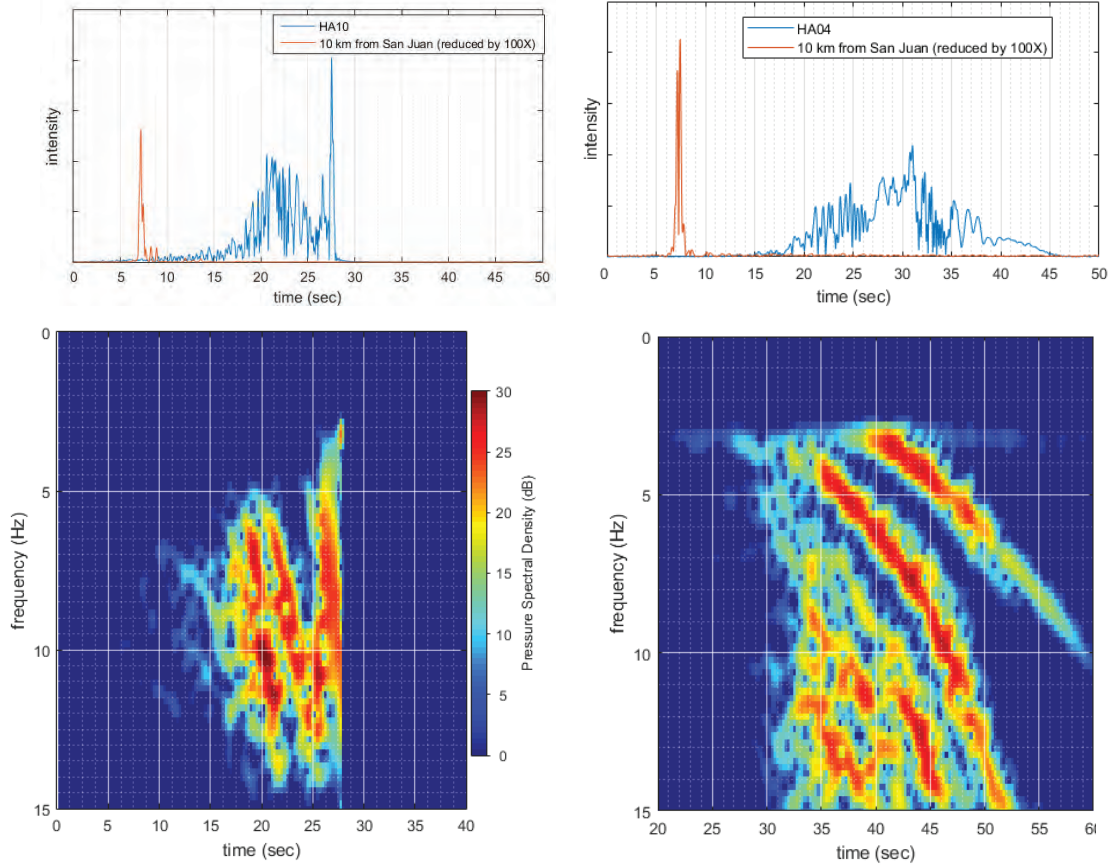


Fig. 3: [left] Synthesized impulse pressure as received 10 km from the San Juan location and HA10, and [right] at 10 km and HA04. Vertical axis is intensity on a linear scale, and level at 10 km is divided by 100. Lower time-frequency plots are the corresponding pressure spectral density at HA10 and HA04 (decibel units).

An alternative and computationally fast model of propagation is based on adiabatic mode theory (adiabatic implies no energy is exchanged between modes). The dispersion characteristics of the *San Juan* impulse at the CTBTO stations show distinct mode arrivals. A difference in dispersion at the two stations is striking, and it is due to the different oceanography along each path (discussed in the next paragraph). Correct identification of modal arrival times is essential for triangulation through back-propagating of detected arrivals. Arrival times depend on group velocity, and an estimate of arrival time (T_n) for the n^{th} mode is given by,

$$T_n = L \frac{d\bar{k}_n}{d\omega} \quad (1)$$

where L is the distance along the geodesic connecting source and receiver, ω is frequency times 2π , k_n is the horizontal wavenumber of the n^{th} mode and the overbar indicates an average value over the propagation path.

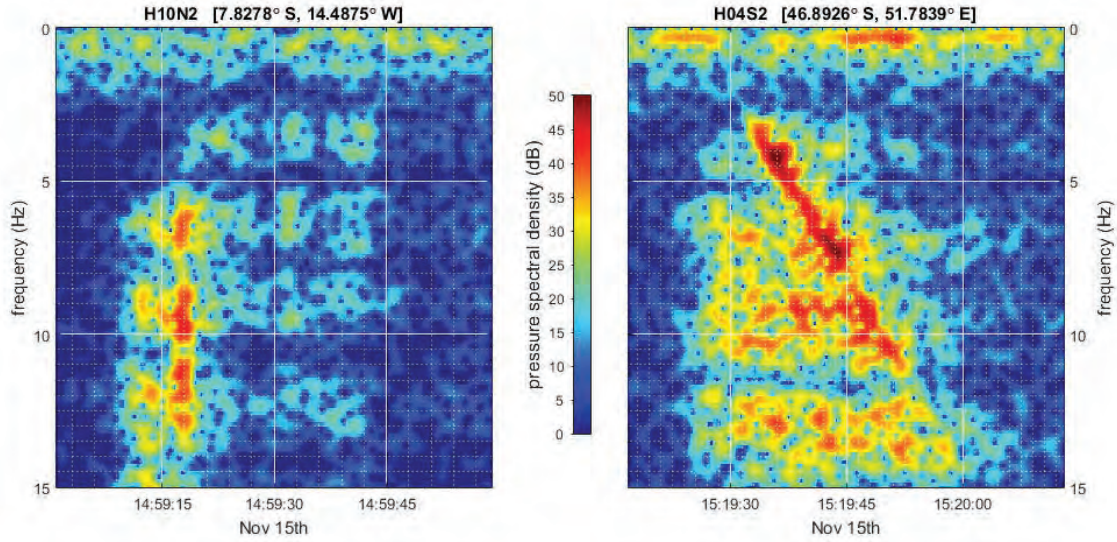


Fig. 4: Time-frequency plot of recorded direct arrival at H10N2 (left) and H04S2 (right)

Propagation to HA10 is primarily within the SOFAR channel, and mode-1 group velocity is effectively frequency independent from 5-15 Hz. Propagation to HA04 is within a surface duct, i.e. reflected from the sea surface and refracted by the deep ocean. Due to the increase in mode number with frequency, mode-1 is pushed closer to horizontal causing its group velocity to slow down linearly with increasing frequency. Group velocity ($d\omega/dk_n$), phase velocity and horizontal wavenumber can be readily calculated via a mode finding routine. With Eq. (1) and mode properties ascertained from the normal mode program KRAKEN [6], and frequency dependence of T_n reproduce the characteristic or mode-1 dispersion. At HA10, the mode-1 arrival is frequency independent, and at HA04 the mode-1 arrival exhibits a 2.5 second delay per Hz [see Fig. 4]. This also confirmed the peak arrival at 10 Hz corresponds to mode-1, and the delay of mode-1 from the onset of signal detection at both stations.

3. PIECEWISE MODELLING OF AZIMUTHALLY REFRACTED ARRIVALS

The 2D model lacks information about the signal coda after the direct arrival (about 30 seconds). The later part of the coda consists of bathymetrically refracted arrivals, and contains valuable information for triangulating sources. To elaborate on this, let us consider the first (and loudest) 3D arrival observed in the HA10 recording. This sound arrives roughly 90 seconds after the first detection, having travelled further to the continental slope where refraction occurred (see dotted red line in Fig. 1).

To model refracted arrivals, horizontal dependence of the adiabatic mode description is modified from a single radial coordinate to two horizontal coordinates (easting and northing). Depth dependence is maintained by the phase and group velocity description of the mode. What drives refraction are gradients in mode phase speed, and thus azimuthal coupling can be modelled with standard 2D ray tracing or PE methods where phase speed is the surrogate for speed of sound.

What we gain with the PE comes at great computational expense. This inherently narrowband simulation method requires a Fourier synthesis to reproduce a timeseries. Note again the long computation time to produce Fig 3, nearly 24-hr for 601 discrete frequency PE simulations. However, narrowband simulations can still be used to identify the path of sound energy. Energy flux streamlines depict the path of energy and are formed by marching in the direction intensity, and divergence of two neighbouring streamlines corresponds to intensity (less energy lost to heat or transmission into the sediment). In free-space, i.e. a uniform medium with no boundaries, streamlines and rays are identical, excepting in the nearfield of complicated sources.[7]

In deep water, low-frequency sound (10 Hz) follows geodesics. Shoaling of sound energy at the continental shelf can be modelled with ray tracing techniques. Ideally the ray connecting a source and receiver is in the direction of the detected energy. However, due to scattering from a realistic bathymetry, finding of such rays is not always possible. To overcome this, a PE solution with a beam starting field is implemented to construct refracted streamlines. The PE embodies the complete dynamics of the refraction process, and by using a beamed source the refracted field is isolated from the direct field [see Fig. 5].

Efficient modelling of 3D arrivals makes use of PE only for the portion of propagation into shallows (the water depth where refraction takes place, which also depends on frequency). The streamline description allows for initiation and then continuation of streamlines with rays (geodesics at 10 Hz) if they propagating into deeper water. Figure 5 shows the continuation of 10 Hz mode-1 with an intensity beam, representing the back propagated energy from H10N2; a clear path exists to the *San Juan* location (star). Of curiosity is a hint of an additional ‘whispering gallery’ path that follows contours of the continental slope. The region where PE computation of the refracted path is needed is roughly 100 km x 100 km, which takes less than a minute to compute.

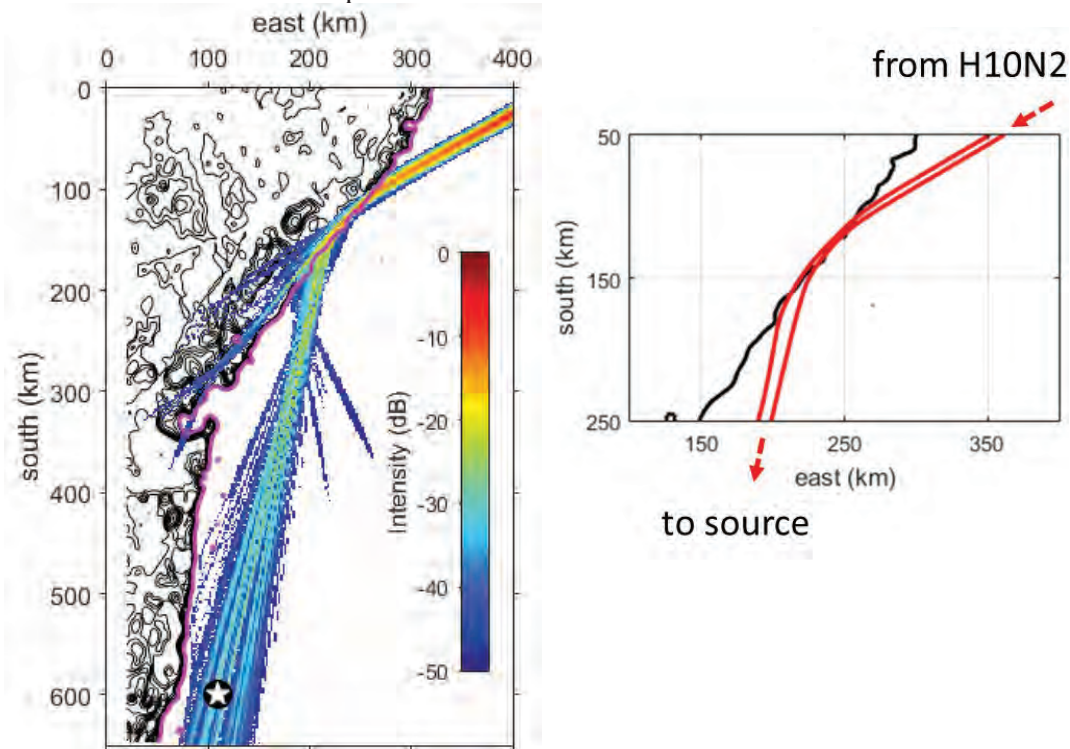


Fig. 5: [Left] Intensity beam of mode-1 at 10 Hz depicting horizontal refraction and energy path to the *San Juan* (star). The input beam direction is a continuation of the geodesic launched from H10N at bearing 221.3° , and the magenta line indicate the 300 m depth contour where bathymetric refraction come into play. [Right] Streamline tube built from the PE simulation, input heading 241° and output heading is 193° .

4. TRIANGULATION OF THE ARA SAN JUAN

With the 3 energy paths shown in Fig. 1 established, two paths to HA10 (Ascension) and one to HA04 (Crozet), the timing of the mode-1 arrival is calculated via Eq. 1. Since mode-1 is characterized by the peak energy arrival at 10 Hz, arrival times are extract from the data. Table 1 outlines the extracted arrival time estimates for mode-1 at 10 Hz used for triangulation. Source triangulation is at the intersection of three isochrones, or the surfaces of equal travel time that are perpendicular to propagation paths. Fig. 6 shows the intersection of the three isochrones, occurring near the location of the *San Juan* (star). With the model parameters, this estimates a source time 13:51:18 UTC.

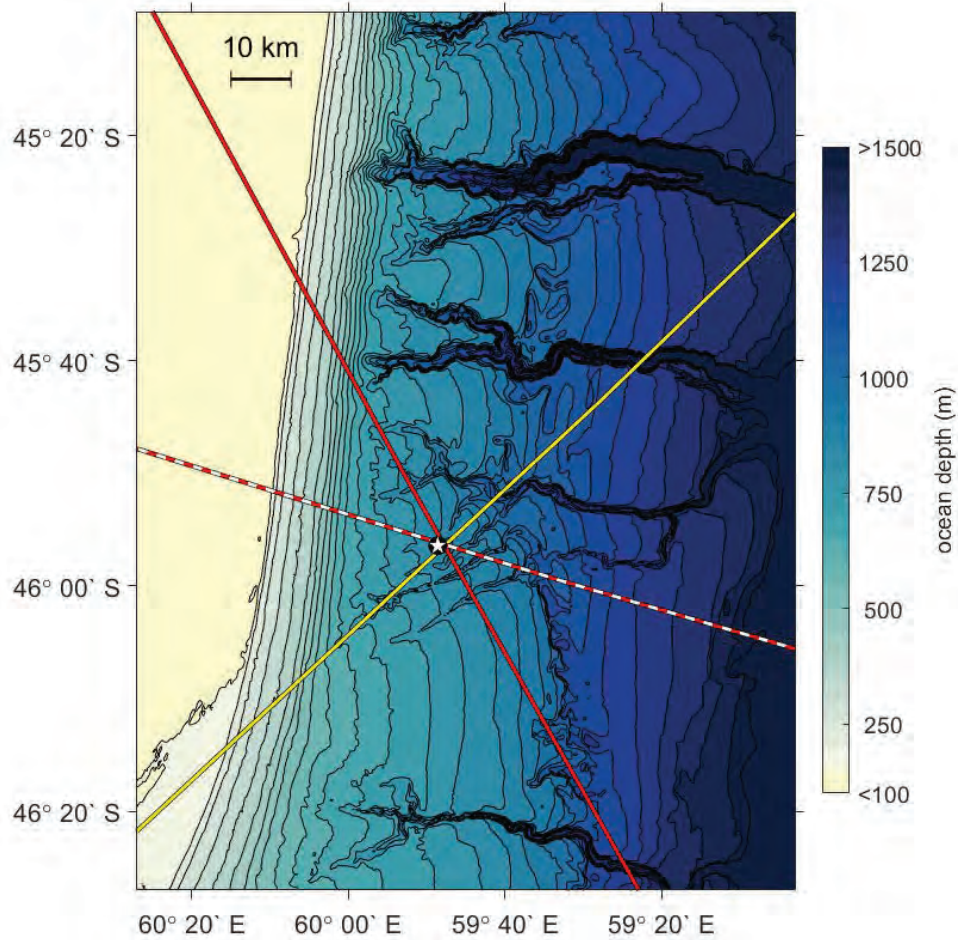


Fig. 6: Triangulation result giving a source time of 13:51:18.

MODE 1 ARRIVAL TIME	NOV 15TH	DEC 1ST
H10N2	14:59:15	21:12:06
H10S2	14:58:04	21:10:51
H04S2	15:19:44	21:33:00
REFRACTED ARRIVAL TIME		
H10N2	15:00:29	21:13:24
H10S2	14:59:23	21:12:15

Table 1: Timing of mode-1 arrivals at 10 Hz used in triangulation

5. SUMMARY AND DISCUSSION

The intense impulsive sound emitted from the submarine, *ARA San Juan*, produced a number of bathymetrically refracted arrivals. A refracted arrival observed at the Ascension Island CTBTO hydroacoustic station was modelled and used to triangulate the sound source from the detections. The energy path of this refracted arrival was reproduced through back-propagating an energy streamline by a piecewise model based on adiabatic modes. By design, azimuthal dependence of streamlines are only calculated with a computationally expensive PE where refraction occurs (at 10 Hz this is in water depth less than 300 m).

Although only one 3D path is detailed here, this technique can be applied to model additional 3D arrivals in the arrival coda and reduce uncertainty in triangulation. The beamed sources with a PE computation addresses complicated propagation the continental slope, but also applies to modelling the modulation of direct propagation around seamounts. Furthermore, this beamed energy technique can build a transfer function to account for refraction (i.e. change in propagation direction) caused by bathymetry surrounding the CTBTO stations.

6. ACKNOWLEDGEMENTS

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Source triangulation utilizing three-dimensional arrivals: Application to the search for the *ARA San Juan* submarine

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On Nov. 15, 2017, an intense acoustic event coincident with the disappearance of the Argentine navy submarine, *ARA (Armada Argentina) San Juan*, was recorded on the hydroacoustic network established to enforce compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Analysis by Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) scientists, based on two hydroacoustic and one seismic detection, provided a likely origin within an error ellipse of 19 km by 12 km; analysis based solely on the main arrival detected at the two hydroacoustic stations gave an error ellipse of ~ 500 km by ~ 25 km [Nielsen, Zampolli, Le Bras, Mialle, Bittner, Poplavskiy, Rozhkov, Haralabus, Tomuta, Bell, and Grenard, in *European Geosciences Union General Assembly*, Vol. 20, EGU2018-18559 (2018)]. The large major axis depends on uncertainty in establishing the event time, while the minor axis depends on precision in the ocean state estimate used to model propagation speed. This paper demonstrates how three-dimensional (3-D) propagation features can also be used in source triangulation, in particular when no seismic detection is available. A mode-based 3-D propagation model is implemented to reconstruct the propagation path of a 3-D arrival bathymetrically refracted from the continental slope. This additional arrival provides a third (virtual) station to decouple the location and time of the event and triangulate the event. This improvement is commensurate with the CTBTO analysis, but does not rely on the additional seismic station detection. © 2019 Acoustical Society of America.

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Pages: 2104–2112

I. INTRODUCTION

On Nov. 15, 2017, an intense signal was detected on an underwater acoustic hydrophone network, coincident with the disappearance of the Argentine navy submarine *ARA San Juan*. The purpose-built acoustic network is part of the larger global International Monitoring System (IMS) operated and maintained by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to verify compliance with the treaty. This continuous, real-time acoustic monitoring of the world's oceans provided crucial evidence to find the missing submarine. Analysis of the signal detected at two stations, HA10 at Ascension Island in the Mid-Atlantic and the other HA04 at the Crozet Islands (Ile de la Possession) in the Southern Indian Ocean, provided a location where a search effort ensued (see Fig. 1). A significant refinement, established by timing of a land-based seismic detection, reduced this search area to a circle of 20 km radius.¹ Unfortunately, even though the initial search effort encompassed the location where the *ARA San Juan* was eventually found in 2018, it was unsuccessful at locating the submarine.

In September of the following year, the search effort was restarted by the seabed exploration company Ocean Infinity. After searching the high priority area established by the CTBTO findings,¹ the author was contacted to provide a confirmation of this location. One striking feature in these recordings are three-dimensional (3-D) propagation features observed at HA10,¹ manifest as delayed arrivals with different azimuth than the primary, main arrival. The highest

amplitude of these delayed arrivals corresponds to acoustic energy bathymetrically refracted,² redirected seaward through multiple bottom interactions as the wavefronts propagated up the continental slope.³ While this observation ruled out possible locations on the shelf (as sources there do not produce refracted arrivals), the timing of these signals, as will be shown, is of great utility for source triangulation. Exactly a year and a day after *ARA San Juan*'s disappearance, the submarine was discovered following this extensive 2+ month effort to acoustically map the ocean floor.⁴

In an attempt to refine the location and confirm the CTBTO analysis, an air-dropped depth-charge was deployed on Dec. 1, 2017 by the Argentine military in the same region [46° S, 60° W]. As will be shown, deployment of the depth charge as a known source was a good idea. Not only did it confirm the signal characteristics of an impulsive signal that propagated 8000 km range, it allowed for verification of modeled propagation speed. Still, when only the main arrival is considered at two stations, there is ambiguity in when or where the event occurred. To resolve ambiguity in the *San Juan* event origin, CTBTO analysis included detection on a land-based seismic station (TRQA) roughly 120 km north of the origin.¹ This third detection decouples event time and location, however, this same improvement could be made with an additional hydroacoustic detection. Detection on a third hydroacoustic station is not necessary, as distinct propagation paths of the observed 3-D arrivals add “virtual” stations which can satisfy the three detection triangulation requirement.

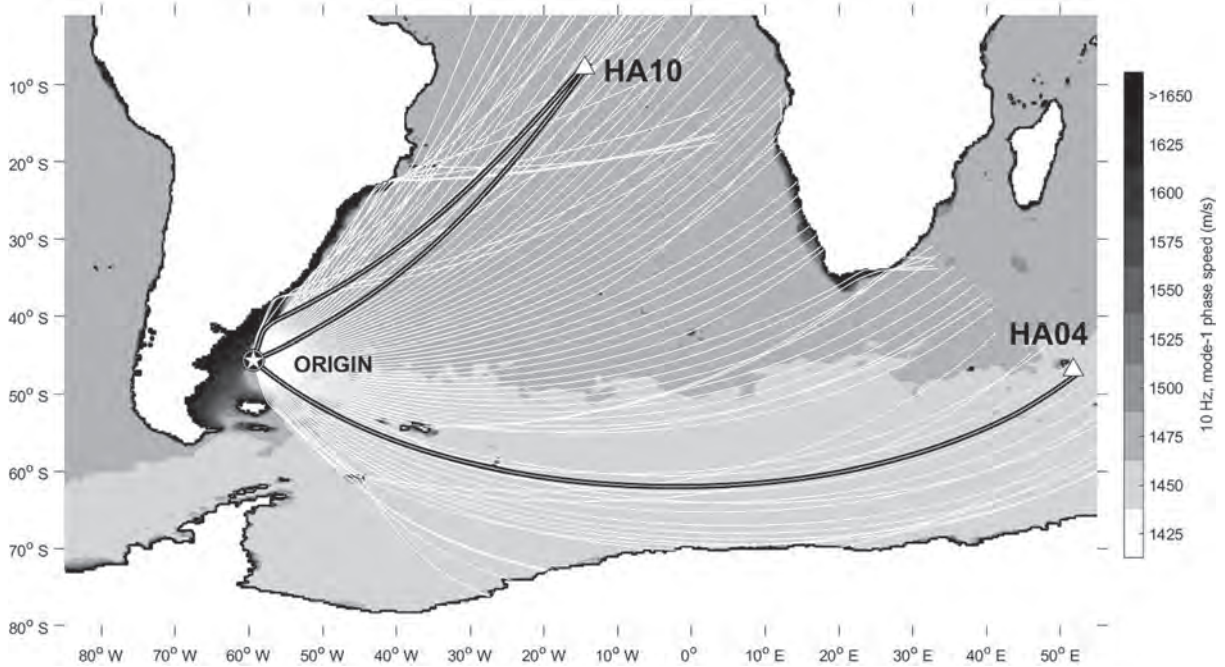


FIG. 1. Horizontal modal-eigenrays (thick black lines) representing 10-Hz mode-1 propagation paths from the origin 46° S, 60° W (star) to CTBTO hydroacoustic stations (triangles). A horizontal modal ray fan (white lines) shows effect of bathymetric refraction from the continental slope, caused by the rapid increase in phase speed (shaded contours).

Virtual stations are built by forming the representative 3-D energy pathlines, connecting the origin of the sound to the hydrophones. Three-dimensional propagation paths are modeled with both a horizontal modal-ray description^{5,6} and

energy pathlines based on an adiabatic-mode parabolic equation (PE) solution.⁷ Modal-rays and energy pathlines are effectively equivalent in deep-water propagation. The PE method is favored for modeling propagation over a realistic

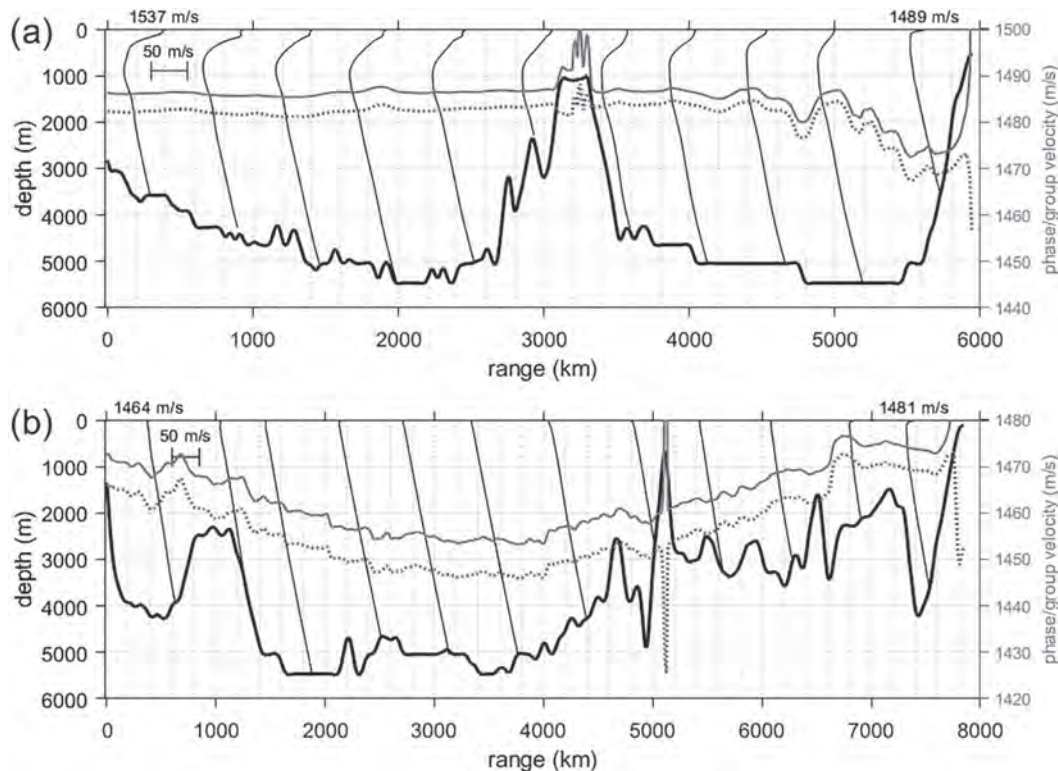


FIG. 2. Sound speed profiles (computed from ECCO2 ocean temperature and salinity model for Nov. 16th, 2017 (Ref. 9)) over the propagation path to 46° S 60° W from: (a) HA10; (b) HA04. Phase velocity (solid gray) and group velocity (dashed gray) correspond to mode-1 at 10-Hz as computed by the numerical code Kraken (Ref. 12).

continental slope, as it provides an unambiguous formulation of acoustic intensity and requires no distinction between a reflection or refraction process.⁸ While the analysis is limited here to the study of the first propagating mode of 10-Hz sound, this reduced model captures the relevant aspects global propagation “involving significant bottom interaction and azimuthal coupling.”⁷

Triangulation is accomplished here in two parts: (1) a directional assessment of sound detected on the multiple hydrophones at each station, and (2) triangulation through the finding the intersection of contours of equal time (or isochrones) representing the possible prior location of signal wavefronts. Geosynchronous timing of this hydroacoustic network allows for great precision in triangulation. Error in localization is ultimately due to uncertainty in precisely when an event occurred, along with under-constrained estimates of the oceanography between the source and hydrophones.

With event time and location defined, the measured propagation speed relates directly to the ocean temperature structure (i.e., ocean tomography). Here, propagation speeds are estimated from the range and depth dependent sound speed (see Fig. 2) derived from a data product developed by the consortium for “Estimating the Circulation and Climate of the Ocean” (ECCO2).⁹ Complimented with direct sampling and space-based oceanographic data, the network and its 20-yr hydroacoustic record is a trove of data for study of trends in ocean temperature.^{10,11} While the focus of this study is on additional information garnered from 3-D arrivals needed for triangulation, it lays the framework to infer the origin and time of sources of opportunity with potential for ocean thermometry using historical and future CTBT data to improve our basic understanding of the under-sampled, deep ocean temperature structure.

The balance of this paper is organized as follows: Section II details the hydroacoustic stations that recorded the *San Juan* and depth-charge event, and characterizes the time and frequency dependent features of the signals. Section III covers the procedure for source triangulation, and addresses uncertainties based on the propagation assumptions. Section IV implements a model to reconstruct one of the observed 3-D acoustic propagation paths arising from refraction by the continental slope, and uses this to triangulate the origin of the two acoustic events. Section V concludes the paper with a short summary and discussion on how 3-D propagation features can reduce uncertainties in localization.

II. DESCRIPTION OF HYDROACOUSTIC RECORDINGS AT: HA10 (ASCENSION) AND HA04 (CROZET)

There are six hydroacoustic (HA) stations integrated into the CTBTO IMS to support verification of member states’ compliance with the CTBT. An HA station consists of either one or two hydrophone triplets, an array of three hydrophones on an equilateral triangle with ~ 2 km baseline separation. This layout provides an unambiguous measurement of sound direction. When combined with geo-synchronized timing of arrivals, multiple stations are used to triangulate the origin of sound sources.

The hydrophones are suspended as close as possible to the axis of the sound channel, near the minimum of sound speed where decreasing ocean temperature is balanced by increasing density. This minimum forms the axis of a sound channel, where sound can propagate without reflection from the seafloor or sea surface. This allows sound to propagate great distances without the scattering and loss mechanisms from incurred by boundary reflections. Although the sound channel structure is not present near the polar region, sound energy still does not interact with the ocean floor where most loss occurs. Here hydrophone triplets are suspended closer to mid-water, at depths ~ 500 m, to provide optimal sensitivity.

The two hydroacoustic stations that sensed the sound events near $[46^\circ \text{ S}, 60^\circ \text{ W}]$ were HA10 at Ascension Island $[8^\circ \text{ S}, 14^\circ 30' \text{ W}]$ in the mid-Atlantic Ocean, and HA04 at the Crozet Islands $[46^\circ 30' \text{ S}, 51^\circ 45' \text{ E}]$ in the Southern Indian Ocean. Both HA10 and HA04 consist of a pair of hydrophone triplets, separated by ~ 200 km, with one triplet located to the north and the other to the south of the island base station providing power and communications (see Fig. 3). During the two-week period Nov. 15 to Dec. 1, 2017, five hydrophones were in operation at HA10 (the complete triplet to the north—H10N, and only two of the three hydrophones at the south—H10S). Only the southern triplet of the HA04 station (H04S) was operational during the Nov. 15th event, although both were operational for the Dec. 1st depth-charge detonation.

Perhaps what is most revealing to the location of these two events are the additional arrivals appearing after the main arrivals at HA10 (Ascension Island). Like the main arrival, these additional 3-D arrivals all exhibit the repetitive spectral feature associated with the source signature. In fact, ten of such late arrivals are documented at HA10,¹ although the focus here will be on the most significant of these that occurs ~ 90 s after the direct arrival. This arrival corresponds to acoustic energy refracted from the continental slope, and will be used in triangulation of the sound events. While the HA04 recordings do not have distinct, delayed 3-D arrivals, they exhibit another fascinating propagation feature: an advanced, faster than seawater arrival (see Fig. 4 at 14:59) presumed to be related to propagation through Antarctic ice.¹

A. Features of the Nov. 15, 2017 event

On Nov. 15, 2017, a distinct signal well above the ambient noise level was received at HA10 (peak arrival for H10S at 14:57:57 Coordinated Universal Time (UTC) and for H10N at 14:59:08 UTC) and at HA04 (peak arrival at 15:19:26 UTC) (see Fig. 4). The southern station of HA10 was the first station to detect the signal, and measured the greatest peak pressure, a level of 145 dB re 1 μ Pa. This impulse signal is well-dispersed, with 95% of the energy arriving within 16 s at the south station and within 21 s for the north station. A distinct peak in this signal occurs 4.79 s after the onset for the south station, and after 5.32 s for the north station. This peak is likely associated with the mode-1 arrival, while the earlier arrivals are higher order modes which in deep-water propagation have faster group

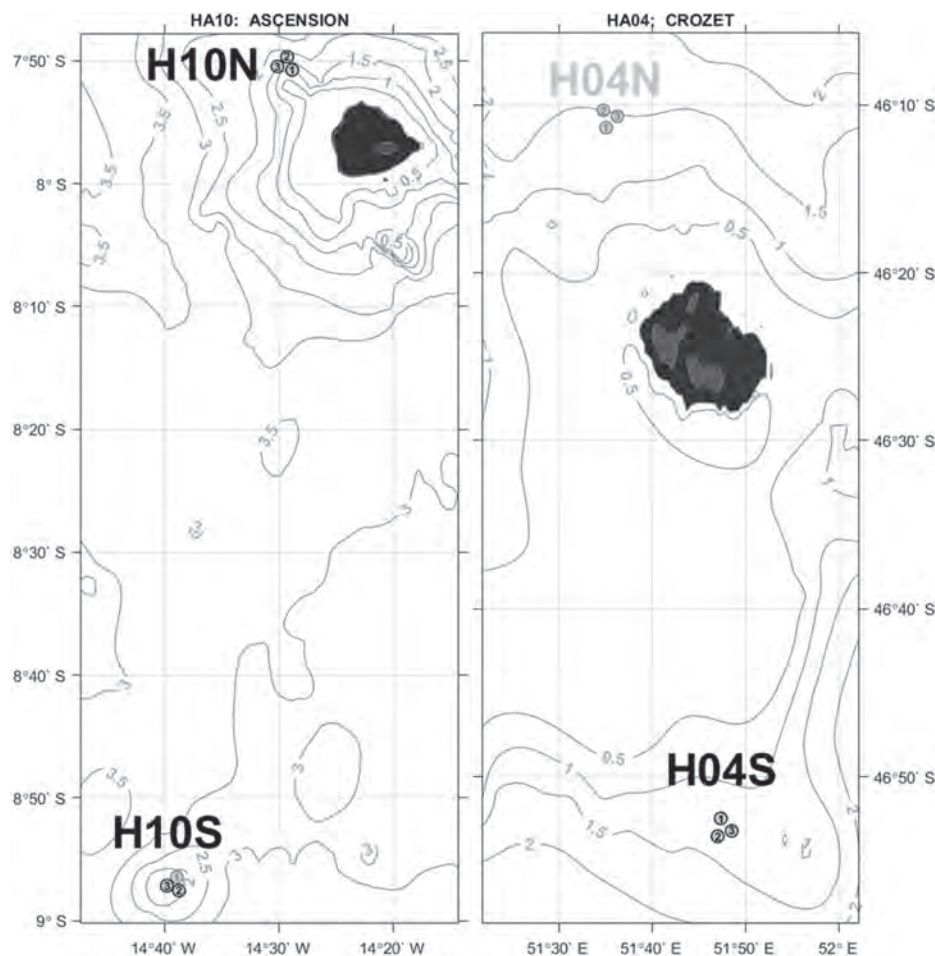


FIG. 3. Bathymetric map with 0.5 km depth contours labels showing the location of CTBT hydrophones (numbered circles). Grayed-out indicates no data on Nov. 15, 2017.

velocities. The difference in dispersion at the north station is due to the additional 100 km of propagation distance, as supported by the ~ 70 s delay relative to the south station.

The signal arriving at HA04 is much more dispersed, over 35 s, and does not have a distinct peak. A defining feature of the signal is the mode-1 dispersion, readily observed in a time-frequency analysis. Due to the slowing group velocity with frequency, the peak of the signal starts at 3 Hz and follows a linear upswep in frequency, at a rate of 0.4 Hz per second.¹³ This feature corresponds to mode-1 of the surface duct formed by the frigid polar waters. In this linear gradient sound-speed profile, the group velocity of mode-1 at lower frequencies is faster (extends deeper into the ocean where sound speed is greater) than at higher frequencies. Remember this dispersion feature, as it is an important aspect of matching the propagation time of mode-1 in the signal.¹⁴

The frequency content appears to be limited to ≥ 3 Hz, with a peak arrival occurring at ~ 10 Hz (see Fig. 5). Since the dispersion of the signals at the two stations look drastically different, the periodic nature of the frequency content was paramount to associating these arrivals to the same event. The periodicity to the spectral levels, Δf , is presumed to be caused by second impulse, or doublet, delayed from the first by $1/\Delta f$. This feature is consistent at the three locations (H10N1, H10S3, and H04S2), and upon auto-correlation or cepstral analysis¹ (i.e., delay spectrum) is revealed to be $335 \text{ ms} \pm 15 \text{ ms}$. Note

that the frequency peaks and valleys at each station are not identical, but both spectra show $\Delta f = 2.9 \text{ Hz}$.

B. Features of the Dec. 1, 2017 depth-charge

On Dec. 1, 2017, two weeks after the incident, an air dropped Mk-54 depth-charge [45 40 S, 59 24 W] was detonated within the general search area. Again, a distinct signal well above the ambient noise level (see Fig. 6) was received at HA10 (first arrival for H10S at 21:10:45 UTC and for H10N at 21:11:57 UTC) and at HA04 (first arrival at 21:32:42 UTC). This detection confirmed the existence of propagation channels to both stations, and the richness of 3-D arrivals at HA10. Dispersion characteristics of this signal are nearly identical to that of the Nov. 15th acoustic event, albeit the signal is less intense. Again, energy concentration was observed in the early part of the HA10 arrivals, while the HA04 arrival is more evenly dispersed. Unlike the *San Juan* signal, the HA04 energy is more evenly distributed in modes, which makes identifying a clear mode-1 “feature” difficult. This is a potential source of error caused by “feature picking” inaccuracy.

Similarly, the Dec 1 depth charge also exhibits a distinct repetitive spectral feature from which to associate azimuthally distributed 3-D arrivals. As the source signature of explosions is well documented, the repetitive feature is believed to be caused by the doublet impulse formed by the

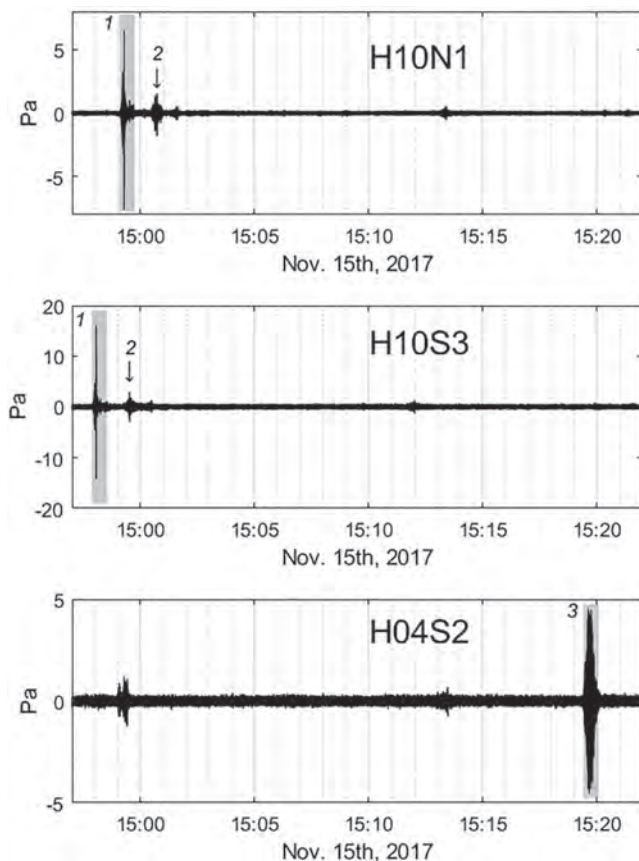


FIG. 4. Sound pressure of ARA *San Juan* acoustic event.

detonation and subsequent bubble collapse. This delay can be predicted based on the charge parameters as¹⁵

$$T = 2.11 \frac{W^{1/3}}{(z + 10.1)^{5/6}}, \quad (1)$$

where W is charge weight (NEW, or net equivalent weight of TNT), z is the charge depth, both in units MKS, and the

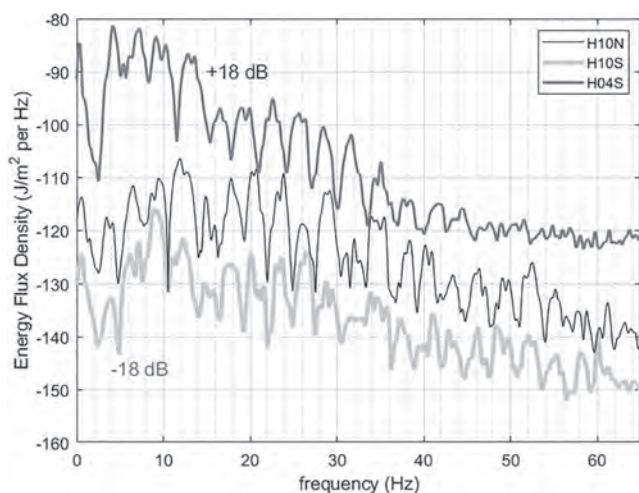


FIG. 5. Spectrum of ARA *San Juan* acoustic event on Nov 15, 2017 observed at H10N (thin), H10S (light gray, offset by -18 dB), and H04S (dark gray, offset by $+18$ dB).

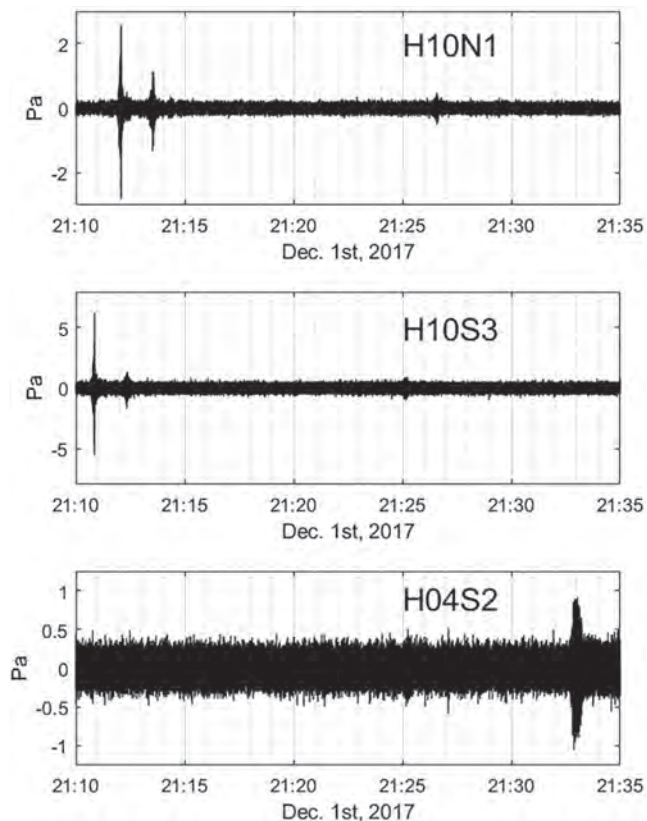


FIG. 6. Sound pressure of Mk-54 depth-charge.

constant 10.1 represents atmospheric pressure in meters of seawater. The parameters of this Mk-54 charge (an ordnance now obsolete) are known: charge weight, 250 lb Torpex multiplied by a 1.3 conversion factor to NEW,¹⁶ $W = 147$ kg NEW; planned detonation depth, $z = 38.1$ m; and notional detonation time 20:04:00 UTC. Equation (1) predicts a bubble period of 440 ms, consistent with the observed value $455 \text{ ms} \pm 2 \text{ ms}$ ($\Delta f = 2.2$ Hz) considering minor errors in conversion factor, charge weight and detonation depth.

Note that although a doublet signature was observed in the Nov. 15th signal associated with the ARA *San Juan* tragedy, there is no absolute evidence showing its natural cause.

III. SOURCE LOCALIZATION

The IMS hydroacoustic network is designed to localize the origin of intense sound anywhere in the oceans of the world. The triad of sensors at each HA station can form a back-azimuth to the source bearing, as input for triangulation. Furthermore, the geosynchronous measurement of arrivals on multiple stations allows for extrapolation of contours of equal travel time, called isochrones, which intersect at the origin of the source. Combined, these inputs produce an area of probable source location (an error ellipse) which can be reduced with detections on additional stations.¹⁷

The bearing of the acoustic arrivals at each station can be formed either via complex spectra, or through delay corresponding to the peak in cross-correlation between two hydrophone stations. The high signal-to-noise ratio (SNR) of the two events proves no distinct advantage of either

method; both produce comparable estimates of arrival angle. The arrival angle, as computed from the delay Δt , and the relative location of the two hydrophones follows the relation

$$\phi = \phi_0 \pm \sin^{-1} \left(\frac{\Delta t \times c}{r_0} \right), \quad (2)$$

where ϕ is the incident bearing, ϕ_0 is the broadside alignment of the two hydrophones, r_0 is the horizontal separation of the hydrophones, and the $\pm$ represents the left–right ambiguity of the estimate. When reversed, these angles form back-azimuths that can be traced along their geodesic to the source location (see Fig. 7).

Ideally, the intersection of these two paths represents the source location such that the timing of the signal (T) satisfies,

$$T = L \frac{d\bar{k}_r}{d\omega}, \quad (3)$$

where $d\bar{k}_r/d\omega$ is the reciprocal average group velocity over the propagation path, which has length L . Source location can be determined without back-azimuths by finding the isochron intersection, which for three stations is distinct and establishes an event time (the received arrival time less the propagation time, T). Computation of isochrones with Eq. (3) requires a global map of group velocity, which again depends on the latitude and longitude (and temporally dependent) sound speed profile. As input, a global model of ocean temperature, salinity and depth are translated to depth dependent sound-speed profiles via empirical equations.¹⁸ The sound-speed profiles along the paths from the two stations show a strong sound channel in the mid-latitudes, sharply transitioning at the circumpolar front to surface duct propagation in the southern latitudes (see Fig. 2). After accounting for the curvature of the Earth through an Earth flattening transformation, the sound speed profiles are then translated to a group velocity to produce the global group velocity map for a particular mode and frequency.

Each pair of hydrophones provides a back-azimuth: three from H10N, one from H10S, and three from H04S, while each hydrophone (eight total for Nov. 15, 2017) provides an arrival time to calculate isochrones. Separation of stations in both in range and azimuth is desirable, as this makes intersection points of back-azimuths and isochrones are distinct. To form isochrones, travel time is integrated along back-azimuths. A representative group velocity of the signal at 10 Hz, taken as the averaged group velocity of mode-1 along the propagation path (see Fig. 2), is 1482 m/s at HA10 and 1455 m/s at HA04. A uniform geoacoustic parameterization representative of the continental slope,^{19,20} is implemented, characterized by a sound speed 1.14 times, and density two times greater than seawater.

Based on a notional event time of 20:04:00 (arrivals outlined in Table I) the isochron intersection is 50 km from the actual source location. The intersection occurs along a line in the east–west direction, for an uncertain arrival time. This orientation is due to the relative location of the stations. If we allow for the notional detonation time to be inaccurate, a

TABLE I. Extracted mode-1 signal parameters.

Station	Nov. 15, 2017	Dec. 1, 2017
Direct		
H10N2	14:59:15/217.2°	21:12:03/217.2°
H10S2	14:58:04/218.2°	21:10:51/218.0°
H04S2	15:19:44/223.3°	21:33:00/224.5°
Refracted		
H10N2	15:00:29/221.2°	21:13:24/221.1°
H10S2	14:59:23/221.7°	21:12:15/221.7°

correction of +31 s brings the isochron intersection to within 3 km. To correct for this offset, the modeled propagation speed can be adjusted (e.g., through modifying ocean temperature) although it is worth noting that this correction may not be physically justifiable.

IV. 3-D MODELING OF PROPAGATION PATHS FOR TRIANGULATION

In order to triangulate with the additional 3-D arrivals, a model of the horizontally refracted propagation path (its energy pathline) is required. One approximate representation of the energy pathline is through horizontally refracted modal-eigenrays. As refraction is caused by gradients in phase speed, e.g., steepness of contour levels in Fig. 1, at 10-Hz refraction is resulting primarily from changes in ocean depth. As such, modal-rays are a great tool to determine *if* sound can reach a particular place in the ocean, but estimating the intensity of refracted arrivals (for example, by examining ray density or through forming a ray-tube) proves difficult. Specifically, as the refraction process involves multiple aspects of acoustic propagation, e.g., forward scattering, diffraction, etc., interpretation of scattered rays from a realistic bathymetry is not straightforward. With these considerations, and to convince the reader that this horizontally refracted propagation path is intense enough to detect on the CTBT hydroacoustic stations, a wave-based numerical code is implemented to identify distinct refracted wavefronts.

Energy pathlines, built from a full-wave simulation of the acoustic intensity vector field, provide an accurate ray-like depiction of the propagation path a wavefront follows.²¹ Here, the vector field is constructed from gridded pressure field simulations via finite-difference approximation to the pressure gradient.²² Results of a “broad-band” simulation are summed (i.e., Fourier synthesis representative of an impulse) to add time-dependence and, given sufficient bandwidth, provides time separation between direct and refracted arrivals to form energy pathlines for each discrete arrival. Here, triangulation of the *San Juan* and depth-charge events is based on pathlines constructed from hybrid single mode-parabolic equation (PE) simulation of the horizontal propagation of mode-1 at 10 Hz.

First, mode-1 properties: horizontal wavenumber, k_r , and group velocity, at 10 Hz are computed over the modeling region (e.g., using a mode-code Kraken¹²). For simplicity, a half-space bottom model is used for these computations (density ratio at the interface of 2, and sound speed ratio of 1.14, and attenuation of 0.25 dB/λ), noting that group

velocity of the refracted path will be most sensitive to this characterization. Next, the horizontal wavenumber (k_r) is used as input to the gridded environment of a PE propagator, specifically phase velocity ($2\pi/\text{Re}\{k_r\}$) as the propagation speed and the imaginary part of k_r as attenuation.²² While this analysis implements the ocean state estimate from ECCO2,⁹ commensurate results can be obtained from tabulated seasonal ocean atlases as the low-frequency propagation is only effected by slowly varying temperature structure.

Figure 8 shows a snapshot in time of the broad-band intensity field, constructed by a summation of the complex narrow-band fields from 9.7 to 10.3 Hz computed in 1/100 Hz increments. Based on this sampling, the concentric rings are wavefronts representing multiple instances of the same source (at the Dec. 1 depth-charge location) repeating every 100 s. Roughly 350 km north of the source, the wavefronts begin to exhibit bathymetric refraction, turning down-slope due to the relative sharp gradient in phase speed as the water shallows approaching the continental shelf (contours in Fig. 8 are at 25 m/s increments of phase speed, between 1475 and 2000 m/s). Still, some sound propagates up onto the shelf, where the propagation is subject to substantial bottom loss corresponding to a large imaginary part of k_r . While this on-shelf sound decays relatively quickly compared to deep-water propagation, the reverse situation—detection of on-shelf sources in deep water—is possible from such intense signals.²³

The vectors shown in Fig. 8 identify the intensity direction of the refracted and direct wavefronts, with those corresponding to the refracted 200 s advanced from the others.

Energy pathlines connect these vectors to the source, constructed by starting at their end (arrows) stepping the field backwards in time applying a phase factor of $e^{i\omega t}$ with t defined in fixed time steps. Depending on which propagation feature is of interest, a recipe to trace a energy pathline is: take an initial point on a wavefront, compute the horizontal intensity, and then back-propagate (step backwards in time) along that direction at the local group velocity. This process is repeated incrementally until the pathline traces the wavefront back to the source, smoothly tracing a path through the bathymetric refraction process. The propagation time is integrated along the pathline following Eq. (3).

Application of this numerical technique to an entire ocean basin is computationally expensive, and some reduction of the field is desirable to efficiently handle 3-D propagation effects. Pathlines are straight and well characterized as rays in deeper water, and application of a full-wave solution is only necessary in the vicinity of the continental shelf, where modes approach cut-off depth. Conceptually, these pathlines form a connection to a piece-wise ray description along which isochrones of refracted paths can be formed. Thus, to maintain efficiency when propagating through blue-water over thousands of kilometers, rays are launched to continue pathlines after the refraction process.¹³

Pathlines in Fig. 8 are incorporated into the triangulation by continuing propagation to HA10 along the geodesics (labeled 1 and 2 in Fig. 8), and in the opposite direction extrapolated beyond the origin. Isochrones are formed for each arrival perpendicular to the respective pathline. Figure 9 shows the triangulation isochron intersection based on the extracted signal parameters in Table I. The triangulation falls

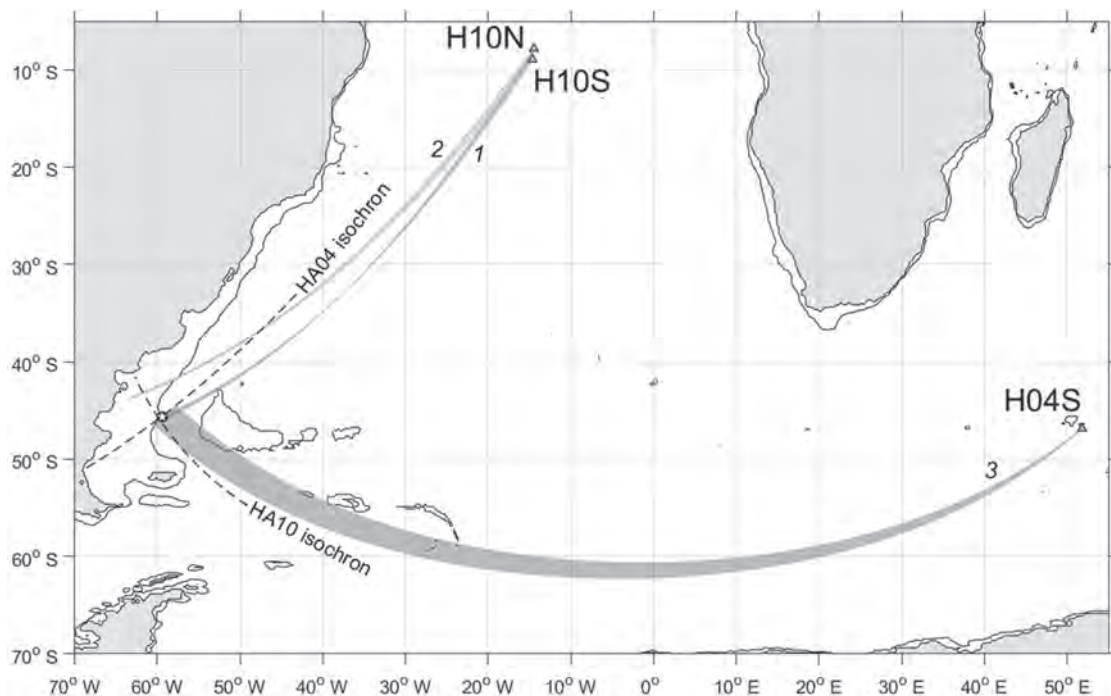


FIG. 7. Projected back-azimuths (shaded arcs) annotated with numbers correspond to the arrivals identified in Fig. 6. Isochrones (dashed lines) of the depth-charge event (star) are drawn perpendicular to the back-azimuth from HA10 (arrival 1) and HA04 (arrival 3) for a notional detonation time 20:04:00 UTC. The contour represents shelf at 250 m depth.

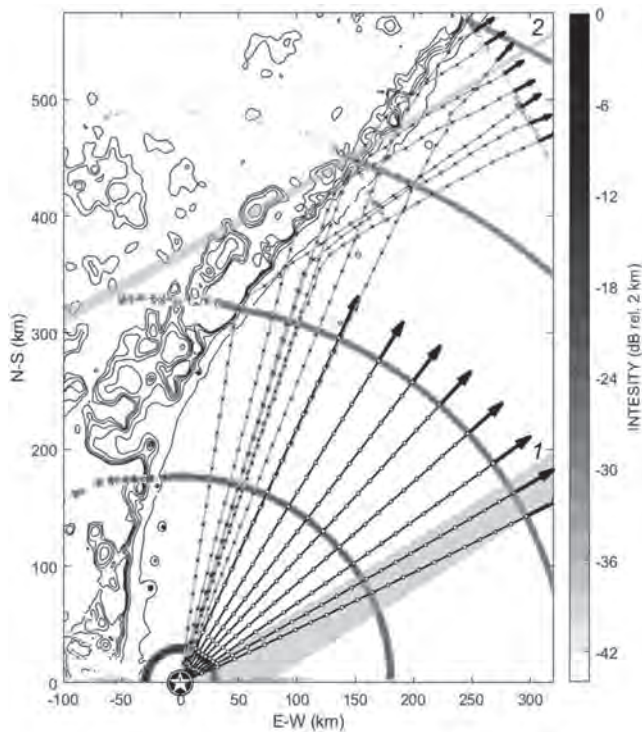


FIG. 8. Wavefronts emanating from depth-charge location (dB rel. intensity at 2 km). Horizontal intensity vectors (arrows) computed at 10 s intervals (markers) trace energy flux pathlines, depicting energy paths of refracted (2-x's) and direct (1-o's) wavefronts [geodesics of detected back-azimuths (Refs. 1 and 2) are shown by shaded beams]. Thin contours represent phase velocity increments of 25 m/s.

within 3 km of the documented depth charge location (star symbol) predicting an event time of 20:04:31, and similarly for the *San Juan* (square symbol) predicting an event time 13:51:16. Uncertainty in triangulation is ultimately due error in the modeled group velocity, or precision in feature picking the mode arrival time within the recorded signals. Uncertainty in triangulation for ± 1 m/s error in group velocity (or 3 s error in feature picking) corresponds to ± 5 km accuracy in triangulation. Factors contributing to this uncertainty include the oceanographic model input, as well as characterization of geoacoustic properties the continental slope sediments. Sediment characterization significantly effects the group velocity where sound interacts with the sea-floor, i.e., ocean depth less than ~ 1000 m for mode-1, 10-Hz sound.

V. SUMMARY AND CONCLUSIONS

This paper detailed the underwater acoustic recordings of a massive acoustic event, made at distances 6000 and 8000 km, relating to the loss of the submarine *ARA San Juan*. These detections provided crucial evidence to define a priority search area,¹ where eventually the wreckage was discovered.⁴ This study was initially motivated to support the search effort and a qualitative assessment was provided based on the observed 3-D arrivals: limit the search area to depths greater than the 250 m contour following the continental slope. The *San Juan* was discovered on the continental slope [45°56.4' W, 59°48.6' S] along the 926 m depth

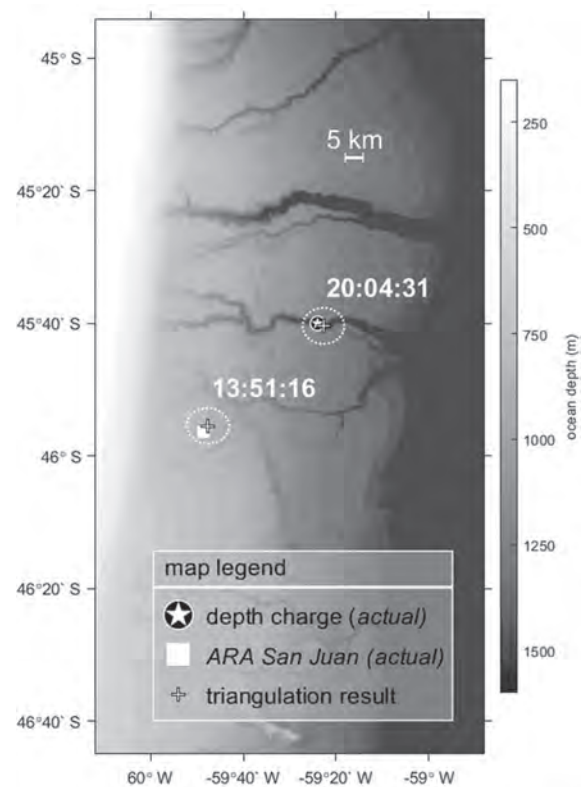


FIG. 9. Bathymetric map of the ocean with location of the *ARA San Juan* (square) and the depth charge deployed on Dec. 1st (star). Triangulation minimum (+) occurs at 20:04:31 for the Dec 1st event, and 13:51:16 for the Nov. 15th event associated with the *San Juan*. The source locations fall within a ~ 5 km uncertainty in triangulation (dotted lines) relative to a 3 s error in feature picking the modal arrival within the signal, or 1 m/s error in group velocity.

contour. Development of a 3-D triangulation technique continued after the *San Juan* was discovered, and that technique is applied here to recordings of that event and a Mk54 depth-charge detonated two weeks after the disappearance in the same general location.

Precision in triangulation improves by including more stations, and at a minimum three arrivals are needed to decouple event time from location. In light of the limited number of hydroacoustic stations in the CTBT network (six total, worldwide), additional “virtual stations” are formed by modeling the propagation paths of 3-D arrivals recorded at a hydroacoustic station. While all source locations may not be advantageous to produce detectable 3-D arrivals, especially for low level signals, the intensity of a nuclear detonation will most certainly produce detectable 3-D arrivals, regardless of location.²⁴ With such 3-D analysis, the CTBT network station density is sufficient to accomplish its mission.

For the triangulation of the events detailed here, one additional station is needed to supplement the main arrival received at two hydroacoustic stations (such a seismic stations¹). Here a virtual station was formed from the first and most intense delayed 3-D arrival, corresponding to sound that propagated up the continental slope and refracted back toward the mid-Atlantic station (HA10). Analysis here was simplified to consider only the mode-1 arrival at 10 Hz, chosen based on its distinct arrival time and at low enough

frequency where oceanic refraction from horizontal temperature gradients is insignificant.⁵ Now with the *San Juan* found, quantitative assessment of the triangulation based on 3-D arrivals is possible. For triangulation, the parameters controlling uncertainty are feature picking, i.e., identifying the modal arrival time within the recorded signals, and the estimates of modal group velocity for each path. Triangulation of both signals was based on modern maps of ocean temperature produced estimates accurate to within 5 km, corresponding to ± 3 s accuracy in feature picking (or 1 m/s error in the group velocity).

From a scientific perspective, recordings of impulsive signals with a precisely known origin (time and location) provide great insight into oceanographic processes—they can be used for ocean tomography (or thermometry, as temperature is the primary driver of sound speed variability). Through matching observed and modeled signals, an iterative process can refine a constrained ocean state estimate by minimizing the error. While in practice known sources are used for tomography, the 3-D triangulation technique presented here provides a framework to do historical thermometry with the CTBT network. With this goal in mind, and complimented with direct sampling and space-based oceanographic measurements, historical and future analysis will necessarily improve our understanding of the deep ocean temperature structure.

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14. ABSTRACT This report covers research completed between 15 March 2018 and 30 September 2021, funded by the ONR grant entitled: "Comprehensive Data Analysis and Modeling of Mid and Low Frequency Sonar in Coastal and Basin-Scale Environments." The primary objective of this ONR grant was to improve understanding of acoustic propagation on two scales, O(10 km) littoral scale and O(1000 km) basin scale. To accomplish this goal, two tasks were undertaken simultaneously: curating a set of data from ocean experiments, and developing a model-framework capable of modeling 3D aspects of the ocean acoustic propagation. This co-development facilitated model/data comparisons and investigations into the effect of oceanography and bathymetry on sound intensity, and the factors driving noise, reverberation and errors in source localization. Three studies are included in this report, and considered generally representative of the technical output of this grant. Two of these study ship-noise; one using the vector field generated by a single ship to inverting for geo-acoustic properties, and the other investigating the ship-traffic noise levels driven by seasonal oceanography (and the economic downturn relating to COVID19). The third study analyzes broadband pulse propagation, the refraction effects driven by bathymetry, and the implications for source localization. All three studies have benefit from the development of model-framework, which facilitated geo-acoustic inversions and noise prediction.					
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