APL-UW Deep Water Propagation 2015-2017: Philippine Sea Data Analysis

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LONG TERM GOALS

Understand how the fundamental statistics of broadband low-frequency acoustical signals evolve during propagation through a dynamically-varying deep ocean.

OBJECTIVES

Current models of signal randomization over long ranges in the deep ocean were developed for and tested in the North Pacific Ocean gyre. The objective of this research is to determine the validity of these models in a region with different oceanographic features, specifically the Philippine Sea.

APPROACH

Philippine Sea Analysis Our approach utilizes a combination of at-sea measurements, theoretical modeling and computational simulations. Our primary measurements are two 60 h transmission exercises over a range of roughly 500 km. We transmitted the signals: the acoustic receptions (and associated receiver details) are provided by Worcester at Scripps, and the environmental measurements at the receiver provided by Colosi at the Naval Postgraduate School. One exercise used the HX554 source and a signal with carrier frequency 81.88 Hz, and the other used the "multiport" source[1] and two simultaneous signals with carriers at 200 and 300 Hz. Each multiport signal had its own m-sequence law, allowing complete separation of the two signals in code space. Here, we assume the acoustic wave equation is valid, and use Monte Carlo simulations as guides — and benchmarks — for analytical expressions describing the evolution — i.e., the "physics" — of statistical properties of the acoustic wavefield.

WORK COMPLETED

Philippine Sea Analysis

- One of the principal reasons for acoustic propagation studies in the Philippine Sea is to understand the performance of sonar models in the region's complex oceanography. Current 4-D models of the "background" ocean state are not perfect and remain an area of active development in the Navy. There remains a mismatch between the state-of-the-art ocean models and the actual ocean. In order to gauge the influence of this mismatch, I plan to use the high-resolution CTD section APL-UW conducted in the Philippine Sea in conjunction with Navy NCOM models.

The first step in this process is to prepare sound speed models from the CTD data and from the NCOM data products. Fig. 1 shows both models. In the ONR PhilSea10 experiment, APL-UW conducted a long CTD section over 510 km, making CTD casts to at least 1500 m every 10 km. The Philippine Sea is known to be an area of energetic oceanographic behavior, filled with mesoscale features propagating westward and shed eastward from the Kuroshio. Mesoscale oceanography is not captured by ocean climatologies, which provide only averages of oceanographic properties. The difference between the measured sound-speed section and a section extracted from the 2009 World Ocean Atlas (WOA09) is shown in the top panel of Fig. 1. Two mesoscale features stand out, a shallower warm-core eddy at range 200 km and a deeper cold core eddy at range 350 km. (Ranges are measured from the APL-UW transmitter station.) The WOA09 climatology clearly does not capture the mesoscale sound speed structure.

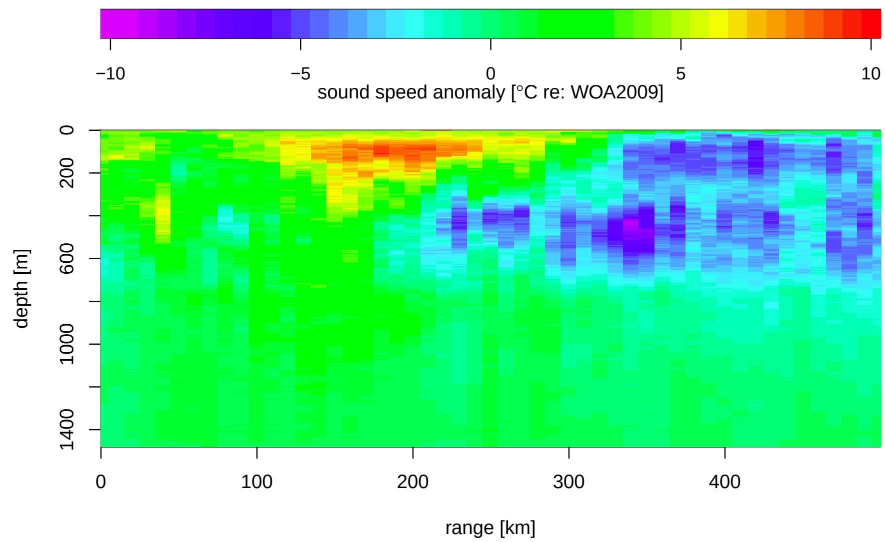
The state-of-the-art in eddy-resolving general circulation models is represented by the models operated for the U.S. Navy by the Naval Oceanographic Office (NAVOCEANO). The best model in operation during the PhilSea10 experiment was the Naval Coastal Ocean Model (NCOM). Fig. 1 shows (bottom panel) the same sound speed section derived from the NCOM prediction of 18 May 2010 00:00:00. For comparison with the measured data, the WOA09 climatology has also been removed from the NCOM sound speed section. The NCOM prediction captures the existence of the two eddies, including their respective depths, although the warm core eddy is not pronounced with this dynamic range. The eddy anomalies in the NCOM model, however, are only about half as large as those actually measured.

These sound channel models will be used in further analysis.

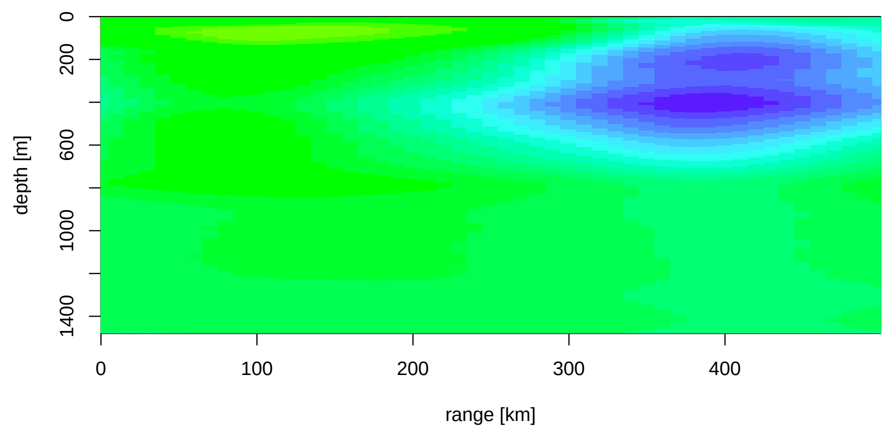
- An undergraduate student, Mr. Robin Mumm (senior, physics), continued to support my repetitive routine data-organization tasks. He has built a "database" of post-processed data products related to the APL PhilSea10 acoustic experiments for sharing among researchers. Since the APL experiments utilized (after pulse compression) pulsed interrogation of the ocean, the primary database elements are the pulses themselves. Four databases have been completed: (1) the "red" multiport signal yielding approximately 9000 timefronts, (2) the corresponding "red" Monte Carlo PE signal (approximately 240 independent realizations, courtesy of Dr. Andrew White, APL.) (3) the "violet" multiport signal yielding approximately 9000 timefronts, (4) the corresponding "violet" Monte Carlo PE signal (approximately 240 independent realizations, courtesy of Dr. Andrew White, APL.)

  The databases are implemented entirely in Matlab and are therefore completely portable.

- All the red and violet multiport pulses, and all the corresponding red and violet MCPE pulses were analyzed for the apparent pulse spread over the 509 km path of the Philippine Sea 2010 experiment. Corresponding calculations were made using the program "Computations of Acoustic Fluctuations from Internal Waves" (CAFI [3].) I compiled these results into a draft JASA manuscript tentatively entitled "Low-frequency Pulse Propagation over 509 km in the Philippine Sea: A Comparison of Observed and Theoretical Pulse Spreading", co-authored with



(a)



(b)

Figure 1: ***Mesoscale sound speed features in the Philippine Sea, May 2010. Both figures show the difference between the sound-speed section and the May WOA09 climatology, which renders subtle features far more distinctly. Top panel: WOA09 versus actual sound-speed measurements[2]. Bottom panel: WOA09 versus the 2010 May 18 00:00:00 NCOM prediction.***

Andrew Ganse, Andrew W. White, James A. Mercer, Matthew A. Dzieciuch, Peter F. Worcester and John A. Colosi and distributed the draft to the co-authors.

North Pacific Ambient Noise Laboratory

- N2N6F24 forwarded to me the Security Classification Guide related to the NPANL effort.
- N2N6F24 commanded a halt to my ambient noise data collection in April 2014, pending a review of procedures involving scientist use of military acoustic system. At their request, I provided a description of my remote data collection systems, my data handling and my data processing. After several rounds of requests and responses, no further direction or decisions have been issued by N2N6F24.
- I copied all the classified ATOC/NPAL data from their original optical media (CDs and DVDs) onto new classified DVDs. The shelf life of standard commercial grade organic optical media is about 3 - 5 years. This archive — which of course uses COTS optical media — dates back to 1994. All the data were recovered and transferred to new classified (SECRET) media, which were properly marked and transferred to APL Security to be inventoried. All original media (1231 CDs and DVDs) were released to APL Security and scheduled for destruction. In addition, 136 copies of original unclassified media were also eliminated in order to reduce unnecessary data storage.
- I updated all the ambient noise data sets by processing all recent data for seven North Pacific receiver systems. The data from these systems have never been published. These datasets contain data from roughly 1995 to 2012 and are now complete. Three channels were collected at each receiver, which we call streams A, B and C. In addition, daily RMS levels were also collected. I use these daily RMS levels to determine the "gain anomaly" between the design system gain and the actual system gain. I have found that the latter differs from the former by as much as $\pm$ 5 dB due to hardware maintenance issues, and it is vital for careful measurements of ambient noise levels to correct for these fluctuations. Figs 2 through Fig. 7 show the resulting gain anomaly files. The next step in ambient noise processing is to correct each stream for this anomaly, and then merge them into the final estimate of ambient noise level. This will complete the update to the NPANL datasets.

  There remains on the remote computers approximately another year of data for each receiver, but these data cannot be recovered until permission to do so has been issued by N2N6F24.
- I am collaborating with Ms. Lisa Pflug of NAVOCEANO for a comparison of in-situ North Pacific ambient noise levels and levels predicted by the NAVOCEANO noise model DANM with the SAFE shipping database.
- I am collaborating with Dr. Michael Ainslie, TNO, to investigate the link between sea surface temperature in the North Pacific and ambient noise levels. I am providing the ambient noise levels.

Kauai Source

The Kauai source was interrogated in November 2014 and found to be healthy. In March 2015, the remote DOS computer was determined to be dead. Two linux systems, based on the successful design deployed in the Philippine Sea experiments, have been prepared and tested at APL. Replacement of the DOS system with one of the linux systems (the other is an in-house back-up) is scheduled for late summer 2015.

RESULTS

Philippine Sea Analysis

- Andy Ganse prepared and distributed to co-authors a draft of a paper entitled "Deep fades without destructive interference in the Philippine Sea long-range ocean acoustic experiment", with authors Andrew A. Ganse, Rex K. Andrew, Frank S. Henyey, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch. A courtesy copy was sent to John Colosi. This paper is targeted for the JASA Express Letters.
- I compared predictions of log-amplitude variance from the old Munk-Zachariasen theory[5] to observed PhilSea09 measurements[6] and associated Monte Carlo parabolic equation (MCPE) simulations[6]. The latter two statistics were taken from a recent paper by White *et al.*[6]. Comparisons were made for more than a dozen receiver depths (defined by the depths of hydrophones on the Scripps vertical line array) for four resolvable propagation paths, labeled ID−3, ID+4, ID−4 and ID+5, having total turning points 3, 4, 4 and 5, respectively. Plots of the results are shown in Fig. 8. It appears that the Munk-Zachariasen predictions are slightly low, but not significantly low given the error bars.

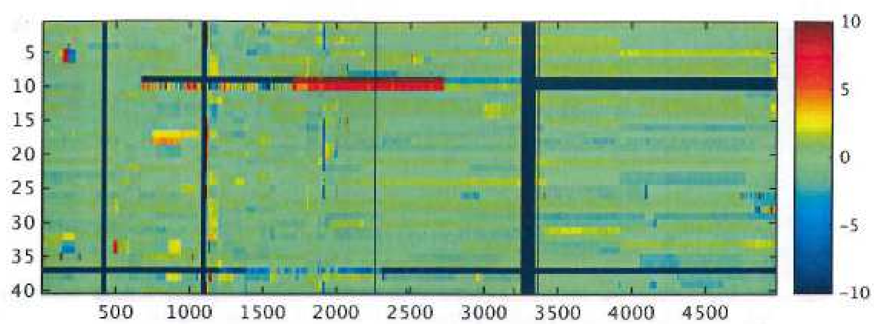


Figure 2: Gain anomalies in decibels versus channel and collection day for system J. Start time: 9/1995. Stop time: 9/2011.

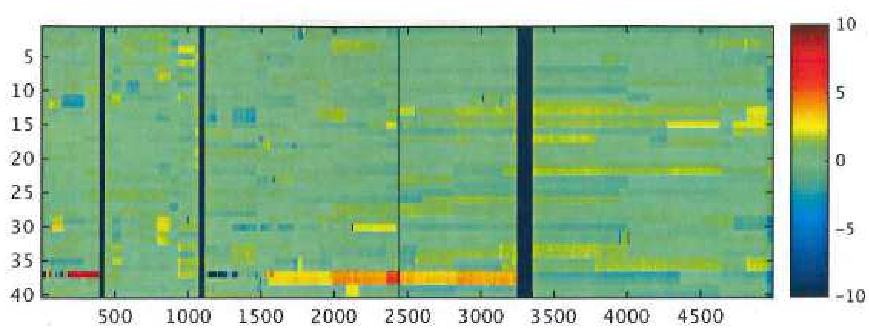


Figure 3: Gain anomalies in decibels versus channel and collection day for system K. Start time: 9/1995. Stop time: 3/2011.

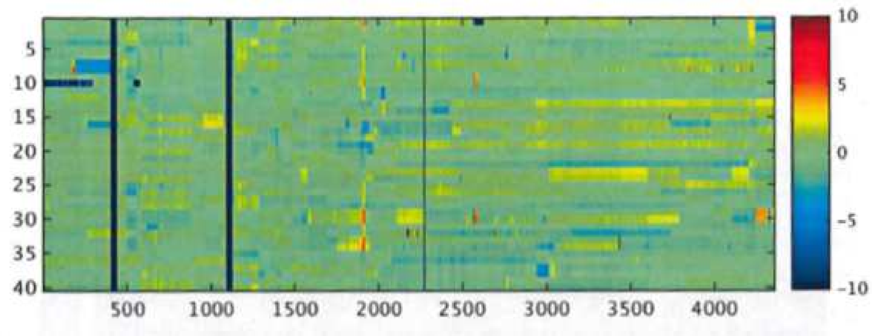


Figure 4: Gain anomalies in decibels versus channel and collection day for system L. Start time: 9/1995. Stop time: 3/2012.

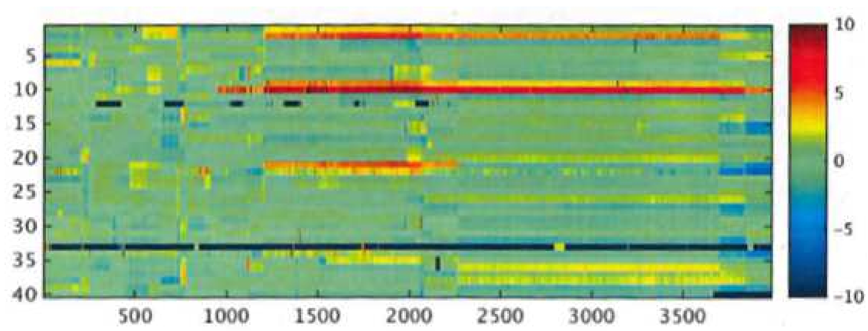


Figure 5: Gain anomalies in decibels versus channel and collection day for system M. Start time: 9/1995. Stop time: 8/2011.

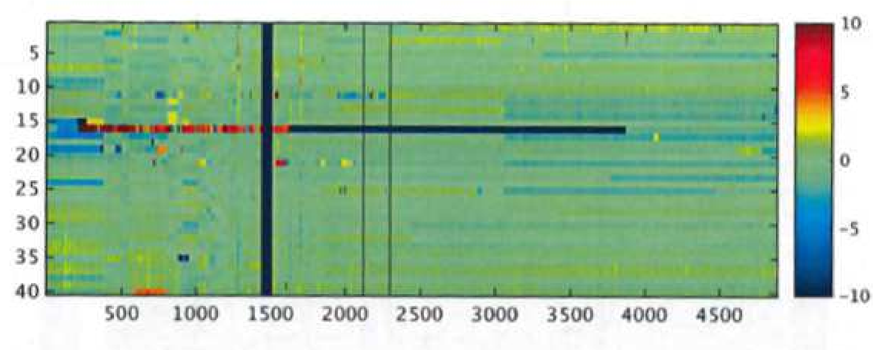


Figure 6: Gain anomalies in decibels versus channel and collection day for system N. Start time: 11/1994. Stop time: 4/2012.

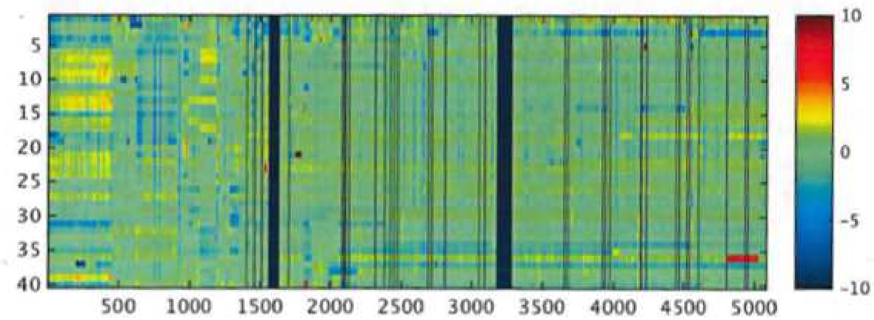


Figure 7: Gain anomalies in decibels versus channel and collection day for system O. Start time: 11/1994. Stop time: 4/2012.

ray ID	MCPE	MZ	MZ/MCPE	$\frac{1}{4}\Lambda\Phi^2$	$\frac{1}{4}\Lambda\Phi^2$/MCPE
-3	0.0473	0.0389	0.82	0.075	1.59
$+4$	0.0961	0.0705	0.73	0.133	1.38
-4	0.0832	0.0725	0.87	0.148	1.78
$+5$	0.0940	0.0830	0.88	0.113	1.20
		ave:	0.83	ave:	1.49

Table 1: Comparison of Rytov-based predictions of log-amplitude variance from MZ and Flatté-Dashen theory against Monte Carlo PE (MCPE) calculations for the four eigenrays studied here. The MCPE, MZ and $\frac{1}{4}\Lambda\Phi^2$ columns are the depth-averaged values. The final row provides the eigenray-averaged ratios of MZ predictions against the MCPE calculations and the CAFI predictions against the MCPE calculations. [Table and caption from Andrew **et al.**, ***" A test of deep water Rytov theory at 284 Hz and 107 km in the Philippine Sea",*** **JASA** ***in press.]***

At the request of an anonymous reviewer, my undergraduate student Robin Mumm and I also calculated the log-amplitude variance as predicted by CAFI for these four paths. Since the MCPE simulations made by White *et al.*[6] were remarkably accurate compared to the measured data, I compared the MCPE predictions against both the Munk-Zachariasen and CAFI calculations. This also provides a three-way comparison using controlled environmental inputs (as opposed to the actual PhilSea09 data, for which the true environmental inputs are not known.) The ratios of the Munk-Zachariasen statistics to the MCPE statistics and the CAFI statistics to the MCPE statistics are shown in Table 1. It appears that CAFI predictions are biased high. Error bars are not shown here: based on Fig. 8, one might assume that the sampling error involved here might weaken the strength of the conclusions.

A paper describing this comparison is in press at *JASA*.

- I used the PhilSea09 observations with the Munk-Zachariasen theory in a crude inverse problem to estimate the strength of the internal waves experienced during the PhilSea09 experiment. Using month-long time series of oceanographic quantities from a dozen CTDs on a deep water mooring, Colosi *et al.*[7] have estimated the strength at 1.4 GM. My earlier work with the Munk-Zachariasen model shows that MZ theory underpredicts the log-amplitude variance. In order to generate an unbiased estimate of internal wave strength, I needed a correction for this MZ theory discrepancy.

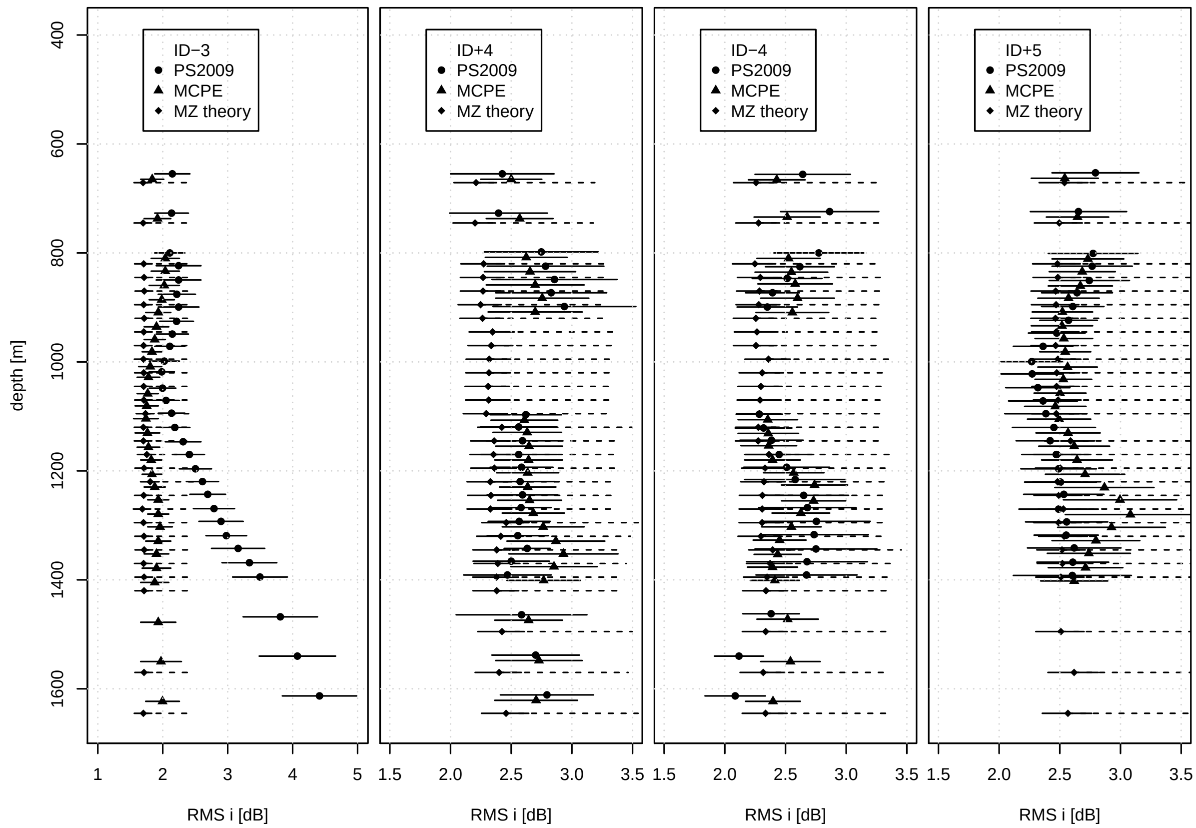


Figure 8: Comparison of log-intensity variances (presented as RMS log-intensity ι) for the Philippine Sea 2009 experiment, 107 km, 284 Hz. Panels left to right correspond to ray path geometries ID$-$3, ID$+$4, ID$-$4, and ID$+$5. Error bar spans for at-sea measurements (PS2009) and Monte Carlo estimates (MCPE) are taken from White **et al.*****[6] and are two standard errors. The at-sea and Monte Carlo error span center points are merely the span midpoints and are only provided for reference; they are not given*** **per se** ***by White*** **et al.** ***See the text for a discussion of the solid MZ prediction error bars. The dashed MZ error bars reflect the lower (left endpoint) and upper (right endpoint) bounds given by White*** **et al.** ***MCPE results offset downward by 10 m, MZ results by 20 m for clarity. Note that the left panel has a different abscissa scale to accommodate the at-sea measurements below about 1000 m. Since*** $\mathrm{var}\,\iota = 4\,\mathrm{var}\,\chi$, ***RMS*** $\iota = (10/\ln 10)\sqrt{\mathrm{var}\,\iota} = (20/\ln 10)\sqrt{\mathrm{var}\,\chi}$ ***in decibels. [Figure and caption from Andrew*** **et al.**, ***" A test of deep water Rytov theory at 284 Hz and 107 km in the Philippine Sea", submitted to*** **JASA.*****]***

In MZ theory (in the unsaturated scattering regime), the log-amplitude variance $\langle\chi^2\rangle$ varies linearly with the product $bE_{GM:x}$ where b is a vertical length scale and $E_{GM:x}$ is a dimensionless scaling term for an internal wave field with unknown GM strength "x". The canonical unity internal wave strength is defined as $E_{GM:1}$. Hence

$$\frac{bE_{GM:x}}{bE_{GM:1}} = \frac{\langle\chi^2\rangle_{W13}}{\langle\chi^2\rangle_{GM:1}}$$

where $\langle\chi^2\rangle_{W13}$ is the observed log-amplitude variance indexed by the actual oceanographic profiles shown in White *et al.*[6], and $\langle\chi^2\rangle_{GM:1}$ is the ideal log-amplitude variance for a unity GM strength ocean. We have $\langle\chi^2\rangle_{W13}$ (this is observed) and we need $\langle\chi^2\rangle_{GM:1}$. It would be nice to use $\langle\chi^2\rangle_{MZ:1}$ (the log-amplitude variance computed easily with the MZ model for a unity strength GM ocean) for $\langle\chi^2\rangle_{GM:1}$, but we have learned that MZ calculations are biased. Fortunately, White *et al.*[6] provides an auxiliary calculation using the Monte Carlo PE, which is very accurate for the PhilSea09 scenario. I can use this result to calibrate the bias error, which is roughly

$$\frac{\langle\chi^2\rangle_{MZ:1.6}}{\langle\chi^2\rangle_{MCPE:1.6}}$$

where the two terms are numerical predictions based on the White *et al.*[6] estimate of GM strength of GM$= 1.6$. The unbiased estimate $\langle\chi^2\rangle_{GM:1}$ is therefore given by

$$\langle\chi^2\rangle_{GM:1} \approx \langle\chi^2\rangle_{MZ:1}\frac{\langle\chi^2\rangle_{MCPE:1.6}}{\langle\chi^2\rangle_{MZ:1.6}}$$

Finally, the "inverse" estimate of the GM strength (given as the ratio of the internal wave field strength to the canonical unity strength) is

$$\frac{bE_{GM:x}}{bE_{GM:1}} \approx \frac{\langle\chi^2\rangle_{W13}}{\langle\chi^2\rangle_{MZ:1}}\frac{\langle\chi^2\rangle_{MZ:1.6}}{\langle\chi^2\rangle_{MCPE:1.6}} \tag{1}$$

Estimates of the depth-averaged value of the ratio are shown in Table 2 for rays ID$+4$, ID-4 and ID$+5$, plus their average. Also shown for comparison are estimates of internal wave field strength provided by Colosi *et al.*[7], White *et al.*[6] and Henyey *et al.*[8]. These results show that the inverse method is fairly accurate, easily differentiating between a GM$= 1$ and a GM$= 1.5$ ocean. Second, the technique takes less at-sea time (3 transmission days) compared to the Colosi method (one month time series) but longer than the Henyey method (a single 4 hour CTD cast.) These results will be compiled into a JASA Express Letter.

- My student and I computed the spread of pulses observed during PhilSea10 for both the "red" and "violet" signals radiated simultaneously by the APL-UW multiport transmitter[1]. These two signals are m-sequences with carrier frequencies of 200 Hz and 300 Hz that correspond to the two multiport resonance frequencies of 210 Hz and 320 Hz. Multiple sections of branches of the timefront observed on the Scripps vertical line array at range 509 km could be resolved, yielding a rich dataset of pulses. Roughly 9000 pulses were transmitted for both the red and violet signals over 50 hrs. I compared the observed pulse spread against spread predictions obtained from CAFI calculations. Additionally, Dr. Andrew White, APL-UW, conducted Monte Carlo parabolic equation simulations of the PhilSea10 scenario at 200 and 300 Hz, and my student extracted

	ray ID			ave
	$+4$	-4	$+5$	
Eq. 1	152 ± 0.04	1.64 ± 0.06	1.45 ± 0.04	1.54 ± 0.05
Colosi et al (2013)				1.4
White et al (2013)				1.6
Henyey et al (2014)				1.7

Table 2: Mean estimates of internal wave field strength (normalized by the canonical strength) inverted from observations of log-amplitude variance, PhilSea09.

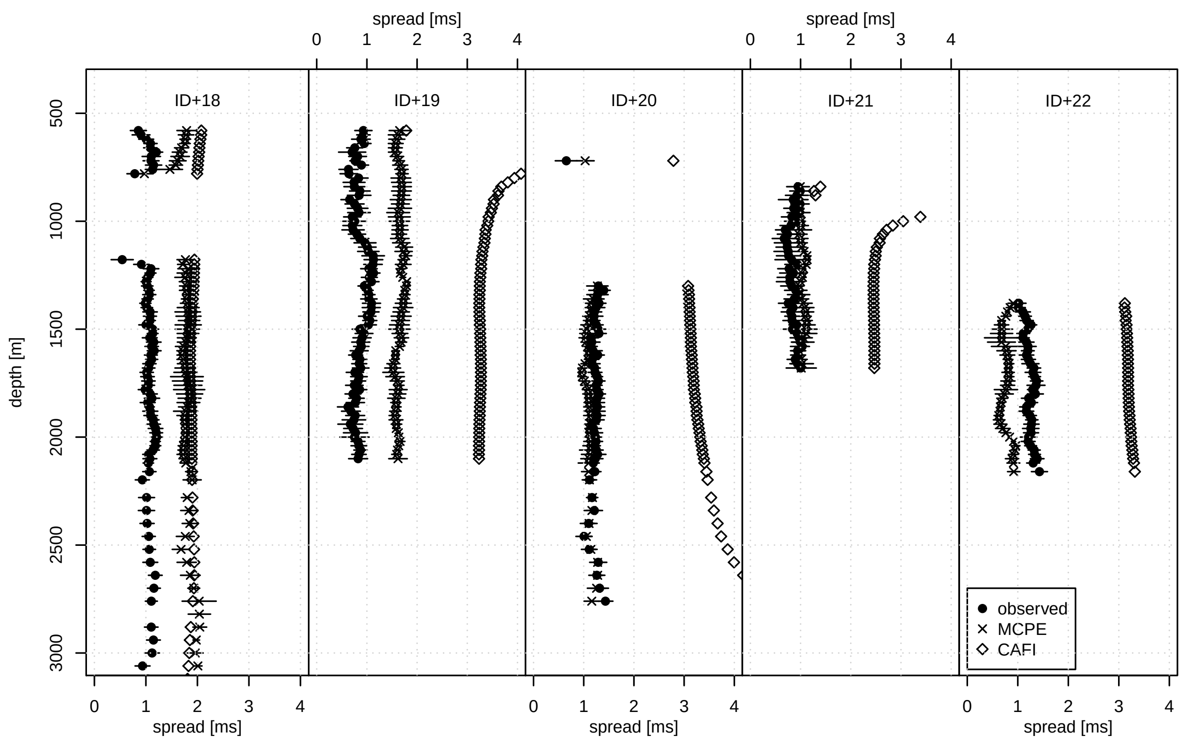


Figure 9: Pulse spreads measured for ray IDs $+18$***,*** $+19$***,*** $+20$***,*** $+21$ ***and*** $+22$ ***for the MP200/TR1446 red signal. Parametric (Gaussian fit) method. Error bars are*** $\pm$ ***two standard errors.***

pulses from the simulated timefronts. This resulted in a dataset of 240 realizations for either 200 or 300 Hz for all corresponding sections of the timefront. The three-way comparisons are shown in Fig. 9 through Fig. 12. These results are based on Gaussian-fits to the observed averaged wander-corrected intensity pulses and suggest that CAFI calculations are quite accurate for 17 to 18 total turning points. This is contrary to results published for much larger ranges. However, for increasing total turning points, the CAFI predictions seem to be developing an increasing over-prediction. This may be related to the longer range over-predictions. [Figures and captions from Andrew *et al.*, “Low-frequency Pulse Propagation over 509 km in the Philippine Sea: A Comparison of Observed and Theoretical Pulse Spreading”, manuscript in preparation.]

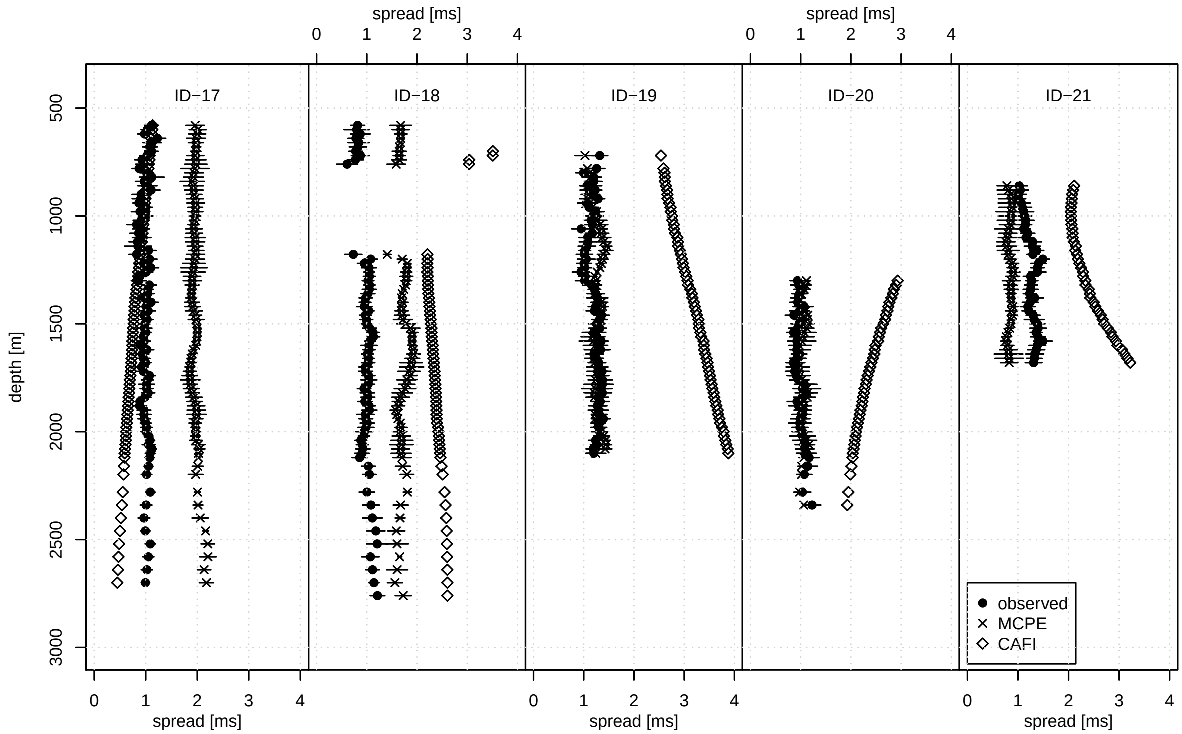


Figure 10: Pulse spreads measured for ray IDs -17, -18, -19, -20 and -21 for the MP200/TR1446 red signal. Parametric (Gaussian fit) method. Error bars are $\pm$ two standard errors.

IMPACT/APPLICATIONS

- The evidence continues to support the hypothesis that the Philippine Sea provides stronger acoustical scattering than does the eastern north Pacific, where we have previously conducted long-range low-frequency acoustic experiments. While we suspected this, some of our models (the internal wave contribution based on density alone, or Munk-Zachariasen theory) continue to under-estimate the scattering strength, which will cause predictions of sonar and long-range acoustic communication performance to be overly optimistic in this regime.

RELATED PROJECTS

- My deep water propagation research involves collaborations with Andrew White (APL), Bruce Howe (UH), John Colosi (NPS) , Tarun Chandrayadula (IITM), and Peter Worcester (SIO). In particular, we worked closely with Dr. White to (1) estimate the PhilSea10 environmental parameters required for his Monte Carlo PE (MCPE) simulations of the PhilSea10 APL experiments, and (2) verify and validate his MCPE computations.
- I am working with Chris Mire and Lisa Pflug, NAVOCEANO, to provide in-situ ambient noise measurements from the North Pacific to improve their ambient noise modeling capability.
- I am supporting Geoff Edelson and Eugene Lavely of BAE Systems, Inc., in the collection and analysis of long range low frequency ocean acoustic propagation signals. This effort supports

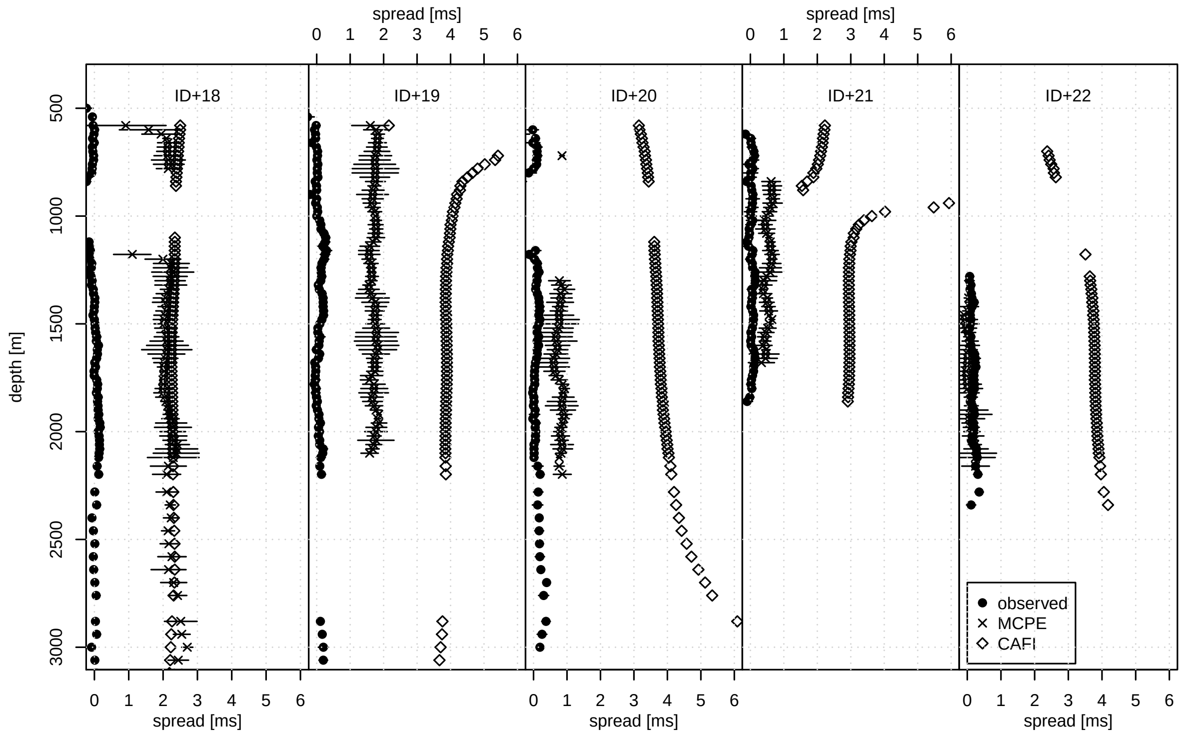


Figure 11: Pulse spreads measured for ray IDs $+18$***,*** $+19$***,*** $+20$***,*** $+21$ ***and*** $+22$ ***for the MP200/TR1446 violet signal. Parametric (Gaussian fit) method. Error bars are*** $\pm$ ***two standard errors.***

DARPA's POSYDON initiative.

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[6] AW White, RK Andrew, JA Mercer, PF Worcester, MA Dzieciuch, and JA Colosi, "Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: observations and modeling I", *J. Acoust. Soc Am.* **134**(4), pp 3347-3358, (2013).

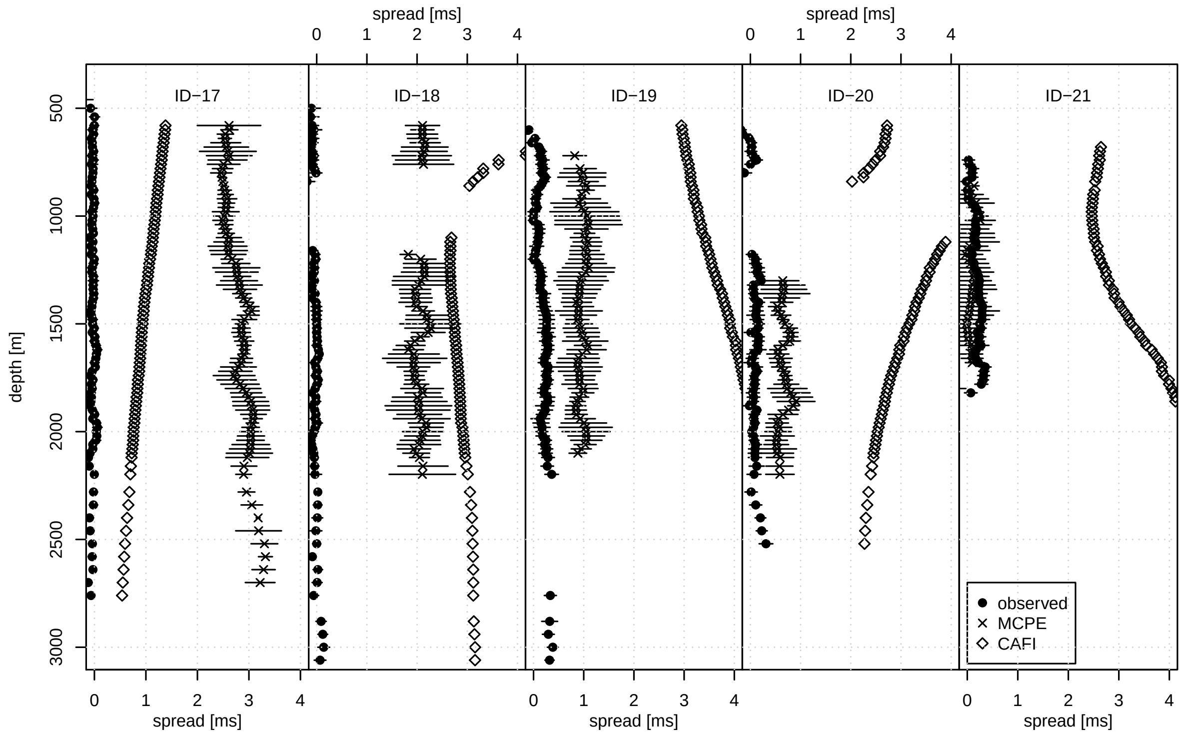

Figure 12: Pulse spreads measured for ray IDs -17***,*** -18***,*** -19***,*** -20 ***and*** -21 ***for the MP200/TR1446 violet signal. Parametric (Gaussian fit) method. Error bars are*** $\pm$ ***two standard errors.***

[7] J. A. Colosi, L. J. van Uffelen, B. D. Cornuelle, M. A. Dzieciuch , P. F. Worcester, B. D. Dushaw and S. R. Ramp, "Observations of sound-speed fluctuations in the western Philippine Sea in the Spring of 2009, *J. Acoustic. Soc. Am.*, **134**, pp 3185-3200, (2013).

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PUBLICATIONS

[1] RK Andrew, AW White, JA Mercer, MA Dzieciuch, PF Worcester, JA Colosi, " A test of deep water Rytov theory at 284 Hz and 107 km in the Philippine Sea", in press at the *J. Acoust. Soc. Am.*