Bottom Interaction in Ocean Acoustic Propagation

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LONG-TERM GOALS

This project addresses "the effects of environmental variability induced by ocean internal waves, internal tides and mesoscale processes, and by bathymetric features including seamounts and ridges, on the stability, statistics, spatial distribution and predictability of broadband acoustic signals..." (quote from the Ocean Acoustics web page). The long-term objective here is to understand the dominant physical mechanisms responsible for propagation and scattering in the deep ocean where the sound channel is not bottom limited. Understanding long range acoustic propagation in the ocean is essential for a broad range of Navy applications such as i) the acoustic detection of ships and submarines at long ranges, ii) avoiding detection of ships and submarines, iii) long range command and communications to submerged assets, and iv) improved understanding of the environment through which the Navy operates.

Bottom interaction plays a significant role in the physics of both short and long-range ocean acoustic propagation and impacts physical models of both signals and ambient noise. As discovered on NPAL04 for controlled sources at long range (500-3200km) in deep water and frequencies around 75Hz, the sound field at the bottom is much more complex than the sound field in the ocean. The deep seafloor arrival pattern is not entirely random, but has some components that are regular, coherent and repeatable.

OBJECTIVES

This project focuses on five tasks: 1) Participation on the PhilSea10 Mobile Operations (MOPS) cruise in July 2010 (three weeks, Kaohsiung- Kaohsiung). 2) Study the physical mechanisms controlling the strength of BR and SRBR paths as a function of frequency in the band 50-400Hz and ranges out to 300km or more. 3) Study the ambient noise as a function of depth and time on the NPAL04 and PhilSea10 DVLAs in the band 2-100Hz. 4) Analyze the controlled source DVLA data acquired on PhilSea09 and PhilSea10 to look for and explain "deep seafloor arrivals". 5) Further analysis of the mysterious "deep seafloor arrivals" on the NPAL04 OBSs. For convenience, we have split these five tasks into two parts, A and B. Part A is the ongoing analysis of the new "deep seafloor arrivals" observed on NPAL04 (Task 5). The first year of Part B includes the cruise participation and analysis of existing DVLA data (Tasks 1 and 3). The second year of Part B focuses on Tasks 2, 3 and 4 using all three DVLA data sets (NPAL04, PhilSea09 and PhilSea10).

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i) Part A: Deep seafloor arrivals on NPAL04

During the 2004 NPAL Experiment in the North Pacific Ocean, in addition to predicted ocean acoustic arrivals and deep shadow zone arrivals (leaking below turning points), we observed "deep seafloor arrivals" that were dominant on the seafloor geophone (at about 5000m depth) but were absent or very weak on the hydrophone array (above 4250m depth). These "deep seafloor arrivals" are a new class of arrivals in ocean acoustics possibly associated with seafloor interface waves.

The goal of our work up to 2009 has been simply to demonstrate the existence of this new class of arrival in long-range ocean acoustic propagation. Now that the community has been convinced that this new class of arrival actually exists the next steps are:

- i) to quantify the characteristics of deep seafloor arrivals as best as possible with existing data,
- ii) to identify the relevant physics or at least the possible physical scenarios,
- iii) to develop predictive models,
- iv) to plan experiments targeted at resolving specific questions and issues related to deep seafloor arrivals
- iv) to think about implications for naval systems.

ii) Part B: BR and SRBR paths, ambient noise and signals on PhilSea09 and PhilSea10

The first science objective here is to understand the physical mechanisms controlling SRBR (surface-reflected, bottom-reflected) strength over long-ranges (>50km) in the 50-400Hz band. This study was initially motivated by the observation on NPAL04 that strong SRBR was observed at 400Hz (~4m wavelength) but not at 75Hz (20m wavelength). Working with Ilya Udovydchenkov over the past year, however, has shown that there are SRBR and BR paths in the LOAPEX data at 75Hz. So we need to rethink the role of SRBR and BR paths in the DSFA story.

The second objective is to study the ambient noise as a function of depth on the DVLA in the band 1-100Hz. Although the passband for the DVLA hydrophones starts at 10Hz, the noise rises so quickly below 10Hz that meaningful ambient noise measurements can still be made down to 1Hz. Wave-wave interaction of gravity waves contributes significantly to ambient noise from about 0.5Hz to 10Hz. Although noise in the band 5-500Hz is traditionally attributed to far-field shipping (Gaul *et al.*, 2006), there is growing evidence that the noise from about 6Hz to 30Hz correlates well with local sea state, in a mechanism possibly involving capillary waves (Farrell and Munk, 2008). Furthermore the observation that the deep seafloor arrivals on NPAL04 in the band 60-90Hz appear to have been scattered as Scholte waves from topographic features, introduces a whole new, topography dependent mechanism to deep seafloor ambient noise studies. In addition to some of the older data sets such as CHURCH OPAL, it would be a good idea to check the new theories against more recent data such as the SVLAs and DVLAs on NPAL04, PhilSea09 and PhilSea10, and the OBSs on NPAL04 and H2O.

The third objective is to study the controlled source arrivals on the deepest hydrophones on the PhilSea09 and PhilsSea10 DVLAs to see if there is any evidence for deep seafloor arrivals in those data sets.

APPROACH

i) Part A: Deep seafloor arrivals on NPAL04

During 2008 and 2009, based on analysis of OBS and DVLA data from NPAL04, I identified a new class of arrivals in long-range ocean acoustic propagation called "deep seafloor arrivals" (Stephen *et al.*, 2009; Stephen *et al.*, 2008). These arrivals are the largest magnitude event observed on OBS geophones in deep water (deeper than about 5000m), they are either not observed or are very weak on the deepest hydrophone in the DVLA (about 750m above the seafloor), and some deep seafloor arrivals occur seconds after the finale arrival. Deep seafloor arrivals appear to be interface waves at the seafloor whose amplitude decays upward into the water column. We believe that deep seafloor arrivals are a ubiquitous feature of long-range sound propagation in the ocean.

The focus of this study in 2010 and 2011 will be continued analysis of the enigmatic, deep sea floor arrivals observed on the controlled source transmissions during NPAL04. Work so far has been based on travel times, (ie the kinematics). More analysis is necessary to define the properties and statistics of these arrivals, particularly the temporal and spatial dependence of the amplitudes and waveforms (ie a dynamics), and there needs to be more of an effort on forward modeling, since existing forward models cannot explain these arrivals.

Some questions to be addressed are:

What are the absolute signal levels on the various receivers?
This is pretty much straight forward if we make a few assumptions. It requires considering processing gain in the replica correlator as well as in the stacking process. The latter requires some thought on coherent versus incoherent stacking and, if coherent stacking, what is the appropriate time window - 10min, 20min ? Is Doppler processing necessary? There are many opinions on these issues even for just the DVLA data and choosing acceptable processing parameters is still a research task. Also there needs to be a factor for converting vertical particle velocity to equivalent pressure. Although most of the time all of the OBS data is self-noise limited, we still need to think about SNR.

What is the transmission loss for deep seafloor arrivals?
Until we get a predictive model specifically for the deep seafloor arrivals, we can boot-strap TL estimates by linking observed levels to the TL from PE models.

What is the phase relationship between pressure and vertical particle velocity?
The phase relationship can be used to distinguish the mode of propagation. For a plane wave in a uniform acoustic medium the ratio of pressure to velocity is simply the acoustic impedance (density times phase velocity) (Jensen *et al.*, 1994) . For interface waves at the seafloor that are proposed to be a significant mechanism in the coupled mode problem (Park *et al.*, 2001), however, the relationship between pressure and particle velocity is more complicated and involves phase shifts depending on the type of interface waves (Rauch, 1980; Sutton and Barstow, 1990). For example, for acoustic waves incident from above the phase shift is zero, but for Scholte (Stoneley) waves the phase shift is pi/2.

What are the consequences for short range (< 500km) propagation?
The results I have shown so far are based on transmissions over 500km range or more. The new physics of deep seafloor arrivals will impact noise models for distant shipping for example. I have not looked carefully at the shorter range data from NPAL04 (50 and 250km) to see what effects the deep

seafloor arrivals may introduce. This will be important for deep seafloor arrival studies in the Philippine Sea Experiment where typical ranges are 350km or less.

ii) Part B: BR and SRBR paths, ambient noise and signals on PhilSea09 and PhilSea10

The first goal here is to study the frequency and range dependence of BR and SRBR paths from grazing to near-normal incidence across the band 50-500Hz. This would be the primary science goal of my participation on the MOPS cruise in July 2010. I would participate on the cruise in Year 1 and I would work up the data (pulse compression, stacking, SNRs, etc) in Year 2.

The second and third goals, studying ambient noise and deep seafloor signals, do not require cruise participation. In the first year, when I am not at sea, I would work on data acquired on the DVLA in PhilSea09 and in the second year I would work on data acquired on the DVLA in PhilSea10. Ambient noise would be studied using conventional spectrogram and RMS energy analysis. Our search for deep shadow zone arrivals would use similar processing and displays to our analysis of the NPAL04 data (time compression, stacking, record sections, etc).

WORK COMPLETED

1) **Participation on the PhilSea10 Mobile Operations (MOPS) cruise in July 2010 (three weeks, Kaohsiung- Kaohsiung) (Part B).** The MOPS cruise was completed in July 2010. The Phil Sea '10 DVLA was not recovered until April 2011. We have not yet requested nor received data from the Phil Sea '10 DVLA. Given the large amount of data that we acquired on the OBSAPS cruise (April-May, 2011) I expect that the focus of our work for the next two years will be on OBSAPS data. At some point reconciling the OBSAPS results with the MOPS receptions on the Phil Sea '10 DVLA will be necessary.

2) **Study the physical mechanisms controlling the strength of BR and SRBR paths as a function of frequency in the band 50-400Hz and ranges out to 300km or more (Part B).** Part B initially involved working with PhilSea09 and PhilSea10 data. Of course the PhilSea10 data, which includes receptions from the MOPS cruise that I sailed on in July 2010, was only recovered in April 2011 and I have not yet requested nor received data from the Phil Sea '10 DVLA. There seems to be a consensus among Phil Sea PIs that I have my hands full with the OBSAPS data and they may be right. Perhaps these issues will be sorted-out at the NPAL meeting in October.

   Meanwhile I have been working with Ilya Udovydchenkov on the observation of SRBR and BR paths in the NPAL04/LOAPEX SVLA data. This is the first discussion of bottom paths in the LOAPEX data that I am aware of. Understanding bottom reflected arrivals is an important component of the DSFA story, so I think this effort is well worthwhile.

3) **Study the ambient noise as a function of depth and time on the NPAL04 and PhilSea10 DVLAs in the band 2-100Hz (Part B).** Although I have a lot of intermediate results on signals and ambient noise levels for DSFAs and other arrivals for NPAL04, I have not completed the work on this so far. The grant does not expire until the end of the calendar year, and I hope to have some results written-up by then. I have not yet received Phil Sea '10 data.

4) **Analyze the controlled source DVLA data acquired on PhilSea09 and PhilSea10 to look for and explain "deep seafloor arrivals" (Part B).** I obtained a preliminary version of one line of PhilSea09 data in Summer 2010 and I was able to check for any evidence of DSFAs that might be useful in planning the OBSAPS cruise. I am not a "blessed" PhilSea09 investigator, however, and I have backed-off on further analysis of this data set (after exchanging many emails officially requesting the data). I have not yet received Phil Sea '10 data.

5) **Further analysis of the mysterious "deep seafloor arrivals" on the NPAL04 OBSs (Part A).** I have been carrying out a comprehensive study of ambient noise and signals on the NPAL04 DVLA (see bullet 3) so that SNRs of PE arrivals on the DVLA could be compared with the SNRs of DSFAs on the OBSs. I have not completed the work on this so far. The grant does not expire until the end of the calendar year, and I hope to have some results written-up by then.

RESULTS

Stephen et al (2009; 2008) focused on stacked traces to just the South OBS and the deepest hydrophone on the DVLA. Last year I compared receptions on all four receivers (South, East, and West OBSs and deepest element on the DVLA) for a single 30sec transmission of the M68.2 sequences at 350m source depth for ranges from 250km to 3200km (Figure 1). As described in the 2009 paper, red indicates "PE predicted" arrivals and blue indicates either "deep shadow zone arrivals"(observed on the DVLA as well as the OBSs) or "deep seafloor arrivals" (primarily observed on the OBSs). For example the blue arrivals at 2sec reduced time for ranges from 500 to 1600km are "deep seafloor arrivals". The deep seafloor arrivals show a consistent pattern, shown in yellow, on all three OBSs. The pattern, observed on the seafloor, is a replica of the arrival pattern on the DVLA hydrophone, 750m above the seafloor, but it is delayed about 2sec.

The traces in Figure 1 are plotted with equal maximum amplitude not absolute units. How strong are the unknown DSFA arrivals, the largest amplitudes on the traces, with respect to the known PE arrivals? How much of the observed SNR is due to loud signal strength and how much is due to quiet ambient noise? None of the transmissions in Figure 1, with ranges from 250 to 3200km, had detectable signals prior to time compression. Nonetheless it is useful to compare SNRs between the OBS and the DVLA hydrophone prior to time compression for a short-range transmission (T50) where the raw transmissions are observable (Figure 2). Prior to time compression the SNR on the vertical geophone (as expressed as pseudo-pressure) is about 19-21dB compared to SNRs of 12-16dB for the hydrophone elements on the deep segment of the DVLA.

Triangulation of the arrival times of the DSFAs at the three OBSs (Figure 1) indicates that the energy is coming from the offline seamount to the north of the geodesics (Figure 3). The top of the seamount is at a comparable depth to the bottom hydrophone of the DVLA which is consistent with the arrival pattern story.

Udovydchenkov et al (in prep) is the first discussion of BR and SRBR arrivals in the LOAPEX data. They show that the 'split' in the observed time front is caused by multi-path reflections from the flat seafloor and from the top of a hill (Figure 4). This is the same hill that is under the geodetic paths (red lines) in Figure 3. Even though these results are for 50km range, compared to the 250-3200km ranges of the DSFAs (Figure 1), it is important to understand the role of BR and SRBR paths in the development the Deep Seafloor Arrival story.

IMPACT/APPLICATIONS

Formerly the acoustic receptions on deep seafloor hydrophone arrays have been interpreted in terms of traditional ocean acoustic paths (refracted-refracted, refracted surface-reflected and surface-reflected bottom reflected) and leakage directly below caustics or turning points (deep shadow zone arrivals) in the ocean sound channel. Our analysis indicates that there is a new, unexplained class of arrivals that appears primarily on deep seafloor receivers. We call these "deep seafloor" arrivals. Deep seafloor arrivals seem to be an interface wave whose amplitude decays upward into the water column. It appears that the interface wave is excited by secondary scattering from a small seamount (Chapman and Marrett, 2006; Dougherty and Stephen, 1988; Schreiner and Dorman, 1990) but this model is not yet fully developed. Understanding the physical mechanisms responsible for these arrivals will be essential for the proper interpretation of long-range receptions on deep seafloor receivers.

TRANSITIONS

Transitions to 32ASW project "Behavior of very low frequency near bottom ambient noise in deep water".

RELATED PROJECTS

LOAPEX - ONR Award Number N00014-1403-1-0181

SPICEX - ONR Award Number N00014-03-1-0182

PhilSea09 -

PhilSea10 -

OBSAPS - ONR Award Number N00014-10-10987

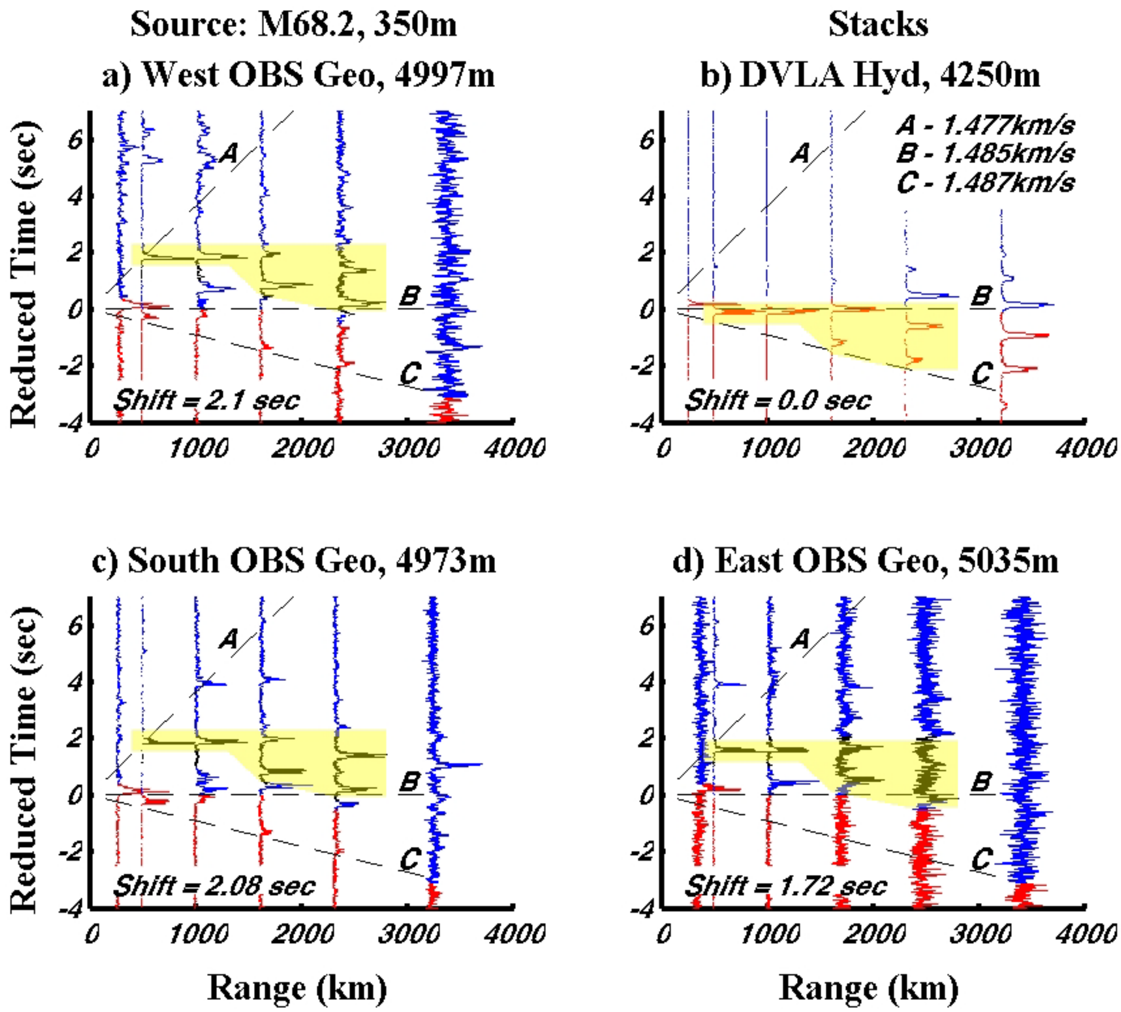

Figure 1: The seafloor arrivals shown in the highlighted yellow regions have a distinctive pattern for all three OBSs. The arrival pattern appears to be a delayed version (by about 2sec) of the pattern on the deepest element of the DVLA. The shifts of these arrivals with respect to the PE arrivals on the DVLA are a constant regardless of range!!! The robustness of these arrivals over all three ocean bottom receivers is remarkable. Dashed lines correspond to three relevant velocities: A- 1.477km/s - the apparent sound speed of the latest arrival at T500, T1000 and T1600, B - 1.485km/s - the apparent sound speed of the largest PE predicted at the deepest hydrophone of the DVLA which seems to separate the known early arrivals from the late unknown arrivals and C - 1.487km/s - the apparent sound speed of the earliest arriving energy at the OBSs and DVLA, which corresponds to the deepest turning rays.

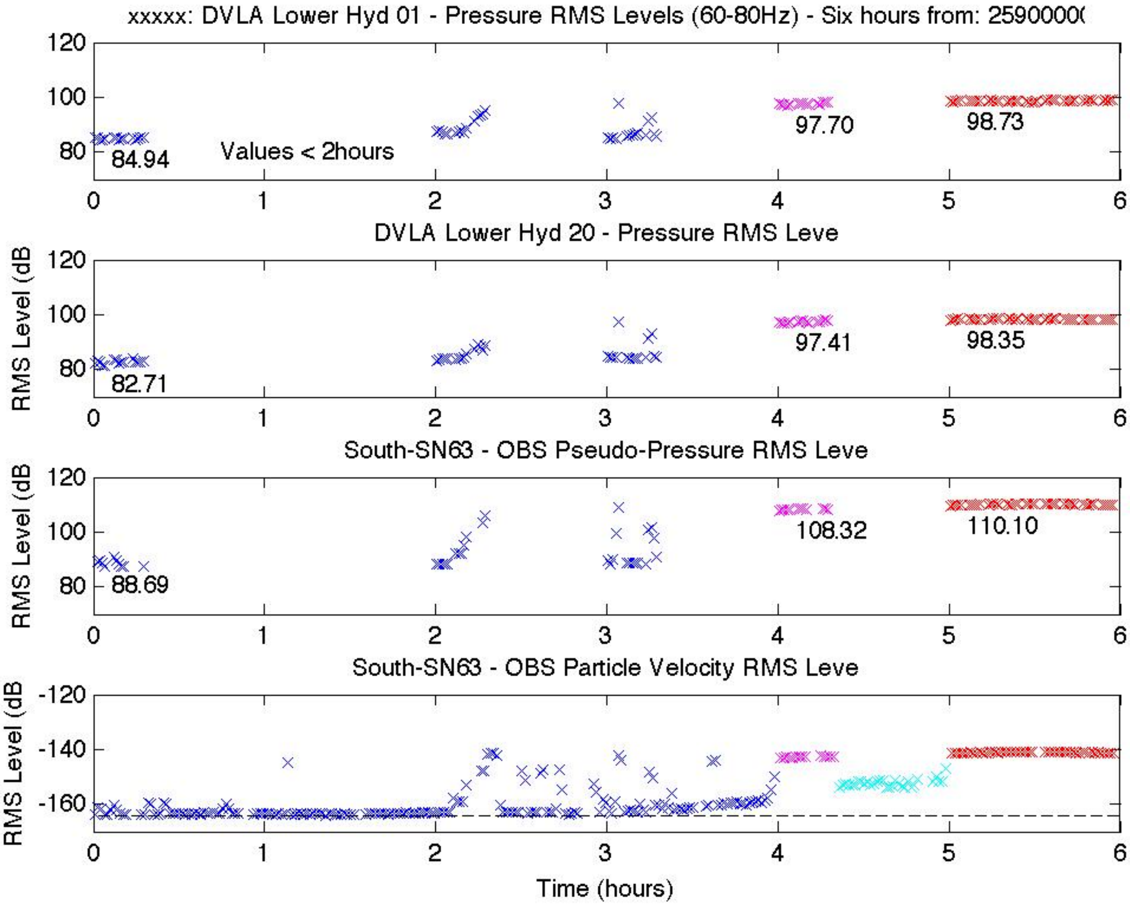

Figure 2: RMS levels in raw time series (before time compression) for the frequency band from 60-80Hz are shown for four sensors for the first six hours on Day 259 in 2004. From top to bottom: the shallowest hydrophone on the lower segment of the DVLA (3,575m depth), the deepest hydrophone on the lower segment of the DVLA (4,250m depth), the "pseudo-pressure" on the South OBS computed from the vertical component geophone data (5,000m depth), and the vertical component geophone data. Blue and cyan indicate intervals where there were no "official" transmissions, magenta where the source was transmitting the PFM800C format, and red where the source was transmitting the M75- 800m format. Apparently some testing of the source was going on in hours 2 and 3. The SNR on the vertical geophone (expressed as pseudo-pressure) is about 19-21dB compared to SNRs of 12-16dB for the hydrophone elements on the DVLA.

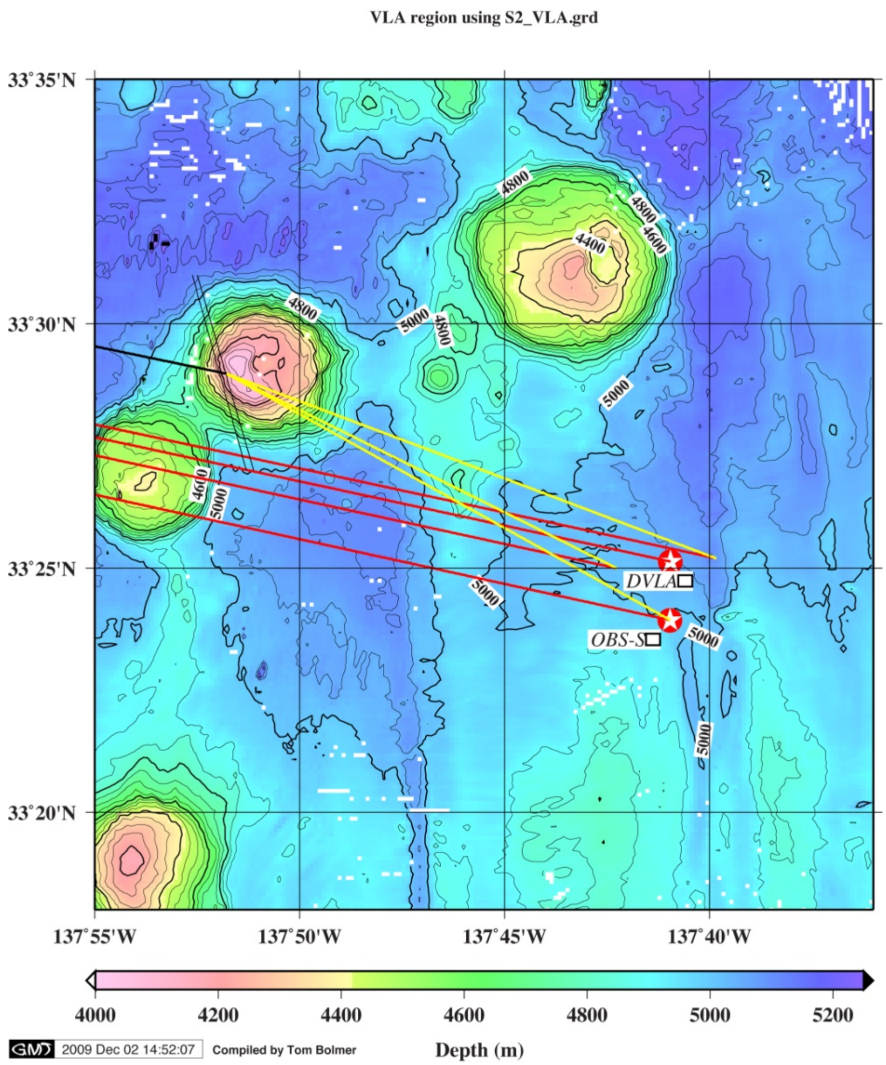

Figure 3: This figure shows the locations of the three OBSs and the DVLA with their geodetic paths (red lines) to the source locations overlain on the swath map bathymetry (Worcester, 2005). All three paths pass over a seamount on the seafloor that is deeper than 4400m. The deep seafloor arrival pattern highlighted in yellow in Figure 1 is consistent with the following propagation path. From all sources from T500 toT2300 the sound travels through the sound channel to seamount B (heavy black line). The sound is then coherently scattered from seamount B and travels to the OBSs as Scholte waves trapped at the seafloor (yellow lines).

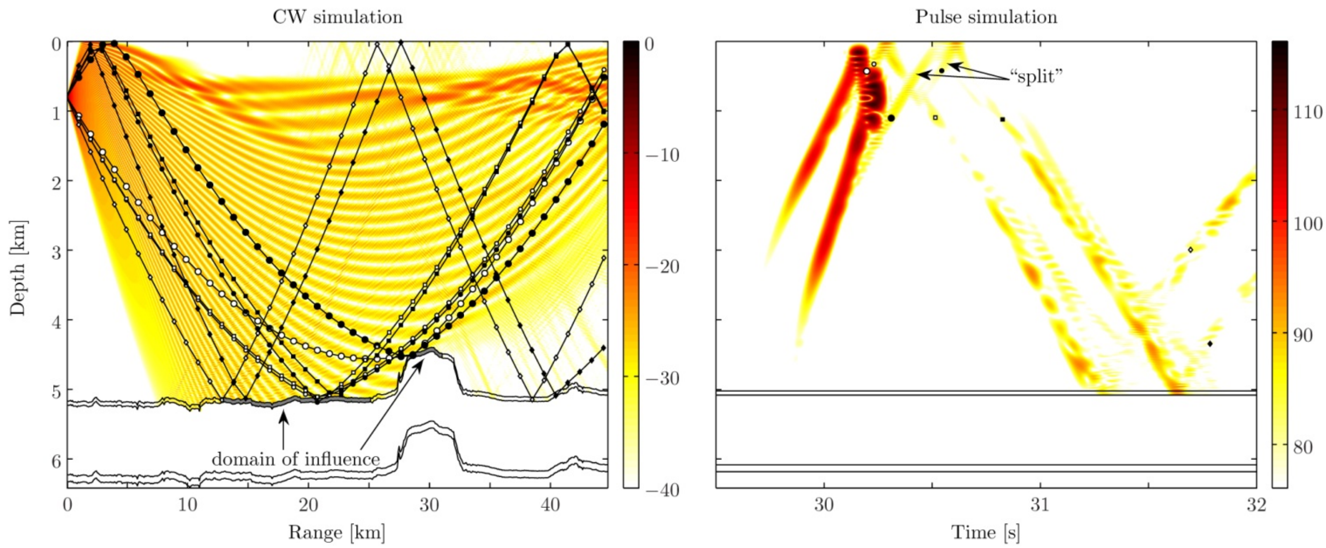

Figure 4: This figure from Udovydchenkov et al (in prep) shows observed data from T50 (time-fronts) on the right and RAM-PE model results (yellow and red color scheme) on the left. Some representative rays are shown on the left and their time-depth location in the data is shown by the same symbol on the right. The 'split' in the observed time front is caused by multi-path reflections from the flat seafloor and from the top of the hill. This is the same hill that is under the geodetic paths (red lines) in Figure 3. This work is the first discussion of BR and SRBR arrivals in the LOAPEX data. Even though these results are for 50km range, compared to the 250-3200km ranges of the DSFAs (Figure 1), it is important to understand the role of BR and SRBR paths in the Deep Seafloor Arrival story.

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PUBLICATIONS

None

HONORS/AWARDS/PRIZES

Ralph Stephen, WHOI, Edward W. and Betty J. Scripps Chair for Excellence in Oceanography, WHOI.