

Performance of Passive and Active Sonars in the Philippine Sea

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LONG-TERM GOALS

We have the long term goals of understanding several aspects of passive and active sonar performance in the Philippine Sea when there is a robust environmental characterization of the sea floor and water column plus accurate source/receiver positions.

OBJECTIVES

The particular objectives for this year was to examine the characteristics of the convergence zone (CZ) at the experiment. 1) We found very abrupt transitions into the CZ. Not all CZ's "focus", *i.e.* sharp edges as we observed in the Philippine Sea. This feature has been noted in Brekhovskikh where he noted that such zones tend to remain clustered for many CZ's. (3) We are concerned with the width of the transitions as well as the stability of signals once a receiver is within a CZ. These factors have significant implications for source localization at CZ ranges. 2) We have analyzed the broadband complex envelope coherence of a sequence of LFM signals while on a constant range over paths with an excess depth to determine the impact, if any, of changes in the sound speed profile.

The Philippine Sea experiments for acoustics and signal processing were executed in two separate cruises in April-May 2009 and in July 2011. There were many source-receiver configurations over the time of the experiment. In 2009 multichannel data were recorded on the FORA (Five octave research array) HLA (horizontal line array) towed by the *R/V Kilo Moana* and the DVLA (Deep Vertical Line Array) moored VLA (vertical line array). Narrowband tones and broadband LFM (linear frequency modulated) chirps were transmitted by a shallow (60 m) J-15/3 at a level of ~ 172 dB re 1 μ Pa @ 1 m and M-sequences by a deep (1000 m) University of Washington MultiPort-200 at a level of 195 dB re 1 μ Pa @ 1 m both from the *R/V Melville*; LFM's were also transmitted from a Webb WRC

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source moored at 1000 *m* at a level of 190 *dB re 1 μ Pa @ 1 m*. In 2011 data were recorded on a water column spanning DVLA from LFM signals transmitted by a shallow J-15/3 towed by the *R/V Revelle* and by five Webb WRC sources moored at 1000 *m*. This was done for many ranges and azimuth tracks from the DVLA.

The results discussed here concern the J-15/3 transmissions to the FORA in 2009. The transmissions to the FORA from the Webb WRC and MP200 as well as the 2011 transmissions to the DVLA are now being analyzed. Unfortunately, there were some equipment problems with the FORA, so travel time analyses have been compromised. Also, weather events (nascent typhoon) led to a premature end of the experiment. The particular objective for this year was to examine the characteristics of the convergence zone (CZ) at the experiment. We found very abrupt transitions into the CZ. Not all CZ's "focus", *i.e.* sharp edges as we observed in the Philippine Sea. This feature has been noted in Brekhovskikh where he noted that such zones tend to remain clustered for many CZ's. (3) We are concerned with the width of the transitions as well as the stability of signals once a receiver is within a CZ. These factors have significant implications for source localization at CZ ranges.

APPROACH

The multichannel array data acquired on the FORA and DVLA were very extensive which have required time intensive signal processing. We have concentrated on the active, broadband processing across and within convergence zones (CZ's). The signal processing is done by beamforming on the source using both conventional and adaptive methods and then matched filtering, or pulse compressing, the LFM. This leads to a peak at the azimuth and range to the LFM source signal. Two features of the performance have been examined: i) The transmissions across a CZ's and ii) the signal coherence while within a CZ. These features were measured by running i) a "STAR" pattern which crossed the CZ's in range yet put the azimuth beam at aft endfire quarter so as to mitigate tow ship self noise and ii) then by running at a constant range using GPS with the FORA at broadside.

These features are motivated by the following. i) The transition across a CZ boundary is often very abrupt so knowledge of the sound speed profile and receiver depth and array orientation permit "CZ localization". While the concept of CZ localization or ranging is not new, the implementation requires understanding the CZ interference as a function of the source and channel parameters. (2), (4) Accurate estimates require a sharp boundary as well as assumptions about the source depth. This SVP leads to especially abrupt CZ edges. The CZ signal is well modeled by four paths from the source: the product four combinations of direct and surface reflections at the source and receiver. The J15/3 source depth was at either 15 *m* or 60 *m* while the FORA tow depth was nominally 240 *m*, so these paths group into two arrival packets according to the source depth. Since we were using wideband signals which resolve travel time, the FORA observes two CZ rings corresponding to the two direct and locally surface reflected paths. For the sound speed profile present the rings were consistently from 58.9 – 60.2 *km* and 63.3 – 65.8 *km* or ≈ 1.3 and 2.5 *km* respectively. (The FORA is only 192 *m* long, so its length does not blur these measurements and the effective range rate of the FORA led to a spatial sampling of less than 200 *m* at the 180 *s* PRI.) ii) The second feature we have examined is the complex (phase coherent) correlation among receptions while the FORA on the *R/V Kilo Moana* was towed at a constant range offset from the J15/3 source on the *R/V Melville* while the separation remained in a CZ. The GPS on board each ship enabled maintaining the navigation within ± 50 *m* for over 13 *hrs*, or a cross range distance of ≈ 110 *km* at the nominal 5 *kts* tow speed.. The objective of this was to determine if the two

paths kept a stable structure or was it modulated by multipath interaction with the bottom or changes in water column mass.

WORK COMPLETED

We have concentrated on the data from the 2009. We have examined the 2011 data to make sure it contained our signals of interest; however, we have not had the time to process much of it. The data in the '09 have been simply too large and filled with some annoying data acquisition issues which have consumed a lot of time. We have implemented beamforming, pulse compression and frequency azimuth (FRAZ) software plus several "peak picking" algorithms often associated with tracking for active sonar signal processing. We have concentrated on the first "STAR" pattern and the constant "CZ offset" tracks. Transmissions to the DVLA and from the T1 source has been initiated. The results are a bit different as much of the data were at multiple CZ's leading to a quite different signal structure because of multipath. As an aside we note that our preliminary measurements suggest strong coherence among the multipaths which suggests that multiple CZ matched field processing (MFP) would be successful consistent with earlier experiments in long range, deep water MFP. (1) We have also applied the beamforming and FRAZ processing for ambient noise analysis; however, this is not presented here because of space and the many options for processing noise data.

We have concentrated on the data analysis. Almost all the literature we have examined concentrates on narrowband tonals or a collection of tonal. While there has been considerable use of broadband signals such as for active sonar and ocean acoustic tomography, there seems to be a paucity of material on the signal amplitude of CZ transitions or the coherence of among multiple transmissions while within a CZ. Future efforts will be on a theoretical basis for our observations to match the numerical parabolic equation modeling.

RESULTS

CZ Transitions and Modeling

Figure 1 is a 2 1/2 D parabolic equation (PE) model for the transmission loss TL from the J15/3 at location SS45. The black line is a super-imposition of the track of the FORA for part of the "STAR" pattern ran to intersect the CZ. The double ring caused the CZ are evident. Note also the very sharp transitions into the CZ. The combination of this sound speed profile and the source/receiver depths imply a very accurate parameter estimation of the range which can be combined with a bearing estimate. This implies a localization within ≈ 1.3 km in range and 2.0 km cross range. There are also indications of "bottom bounce" returns at ranges closer than the CZ and "multiple" ones at ranges farther.

The "zig-zag" black trace superimposed on the TL indicates part of the star pattern of the track of the *R/V Kilo Moana*. For this discussion we are interested starting on the first leg on the point of the star pattern just after exiting the second ring of the CZ at 65 kms. Figure 2 illustrates the receptions for the two LFM bands transmitted by the J15/3 with the source-receiver beneath. The vertical lines indicate the transition of the first CZ edge. The beam outputs were "peak picked" as the reception angle changed during each leg of the star. We note i) the width of each of the CZ bands is very narrow as suggested by the modeling of in Figure 1; ii) the transition into and out of the CZ band is very abrupt (the receptions are aliased "graphically" by the density of the plotting; and iii) the regions in between the CZ when the *R/V Kilo Moana* was closer than the first CZ edge at 59 km is filled with bottom bounce returns. The

predictions of transit times across the CZ are excellent. The model predicts more bottom bounce energy than observed.

Signal Coherence within a CZ

An important measure for an active sonars which try to exploit multiple pulses such as synthetic aperture systems is the coherence of the complex envelopes of the pulse compression filters. This is indicative of the stability of the ray paths between a source and a sonar receivers. We tested this stability using a track geometry whereby the FORA array was towed at constant separation within the first ring of the CZ described above. This track geometry is indicated in Figure 4. The track extended approximately 110 km with the FORA towed at broadside to the source. The excess depth was 4750 m so there was no interfering bathymetry for the CZ paths, *i.e* there were no bottom bounce paths, just RR, RSR and RSSR ones. The paths with a surface reflection near the source are not resolvable by travel time, so effectively there are two signal arrivals. We use a narrowband, or complex, representation of the signals demodulated to 250 Hz, so the output of the matched filter for the LFM signal is the complex envelope of the pulse compressed signal. We want to measure the coherence among all the transmissions, so have calculated the normalized correlation, or coherence, given by

$$\rho_{i,j} = \frac{\max}{\Delta T} \left[\frac{|\int r_i(t)r_j^*(t-\Delta T)dt|^2}{\sqrt{\int |r_i|^2(t)dt \int |r_j|^2(t)dt}} \right]$$

We need to take the "max" over a small time delay alignment, ΔT , on the scale of a few samples, or ± 10 ms or ± 15 m, because small navigation errors. This simply aligns the phase, but does not alter the complex envelope of a signal. Figure 5 illustrates this cross coherence matrix for the 90 – 180 Hz band on the left and 375 – 525 Hz one on the right. We note that there are 150 entries in each matrix which leads to a very compressed presentation. The coherence levels are typically above .8 which is probably the limit imposed by the background noise as there has been no averaging using successive signal. As with all coherence matrices the main diagonal is unity. We can observe a loss of coherence to $\approx .6$ at the late time which can be attributed to an increase in the local wind speed and an increase of the ambient noise. This impact on the high band essentially destroys any coherence. We also note that the source depth was reduced from 60 m to 15 m at 9 hrs when there was a brief interruption transmissions. As expected there is a lot more variability in the high band and there are patches of exceptionally high levels, close to unity, in the low band. The complex coherence is sensitive to phase, so any modulation of interfering paths due to a changing sound speed profile would reduce it. What seems remarkable is the overall level over the extent of the arc which suggests an opportunity for some very wide synthetic aperture methods with a higher PRF and phase locked loop tracking.

IMPACT/APPLICATIONS

There are two potential applications: 1) The very sharp edge of the CZ's at this location in the Philippine Sea could be exploited for accurate source localization. 2) The coherence over very wide extent of CZ receptions suggests an opportunity for synthetic aperture methods for better detection and localization of CZ sources.

REFERENCES

- [1] Baggeroer, A. B., Kuperman, W. A. and Schmidt, H., "Matched field processing: source localization in correlated noise as an optimum parameter estimation problem", *Journal of Ocean Engineering*, vol. 83, [1988]
- [2] Beilis, A., "Convergence zone positions vis ray-mode theory", *J. of the Acoustical Soc.. of America*, vol. 74(1), pp. 171 - 181, [July 1983]
- [3] Brekhovskikh, L. and Lysanov, Y., *Fundamentals of Ocean Acoustics, 3rd Edition*, pp. 58-60, Springer, New York, [2001]
- [4] Galkin, O.P., Kharachennko, E. A. and Shvachko, L. V., "Acoustic field structure in the first oceanic convergence zone for different frequencies in the audio range", *Acoustical Physics*, vol. 46(3), pp. 274 - 283, [2000]

RELATED PROJECTS

1. Vector Sensor Array Signal Processing
N00014-07-12-0050
2. WHOI MURI on acoustic communications
3. PLUS (Persistence Littoral Undersea Surveillance INP), funded at MIT Lincoln Laboratory (CONOPS and vector sensor processing)
4. SSTAG (Submarine Surveillance Technical Advisory Group) for N975)
5. FCP (Future Concepts Program for Design for Undersea Warfare) for COMSUBFOR)

FIGURES

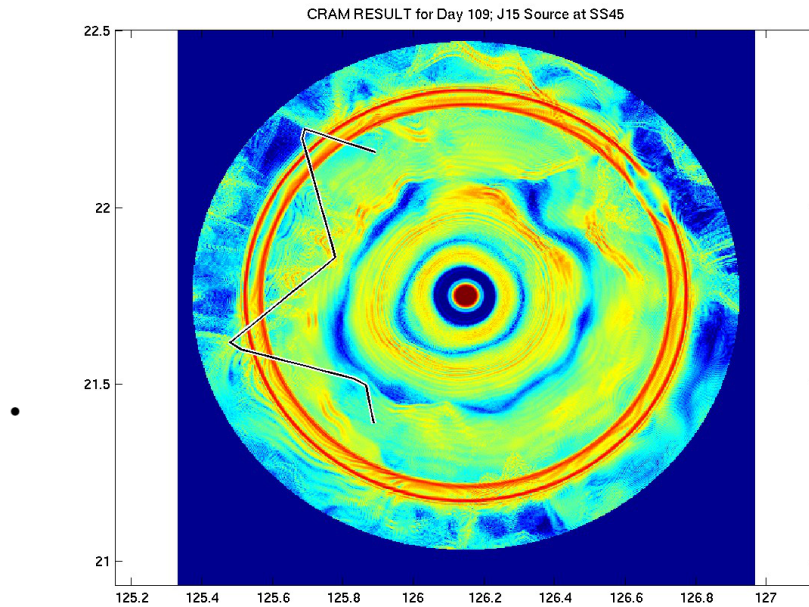


Figure 1: C-RAM (C-RAM) 2 1/2 modeling broadband incoherent TL transmissions from the R/V Melville to the FORA running part of a "STAR" pattern indicated by the black line segments . The source depth was 60 m and the FORA was towed at 240 m. The two CZ rings corresponding to the direct and the surface reflection near the FORA. Inside the CZ rings "shadow zones" (deep blue) and "bottom bounce" returns are evident. (C-RAM courtesy K. Heaney)

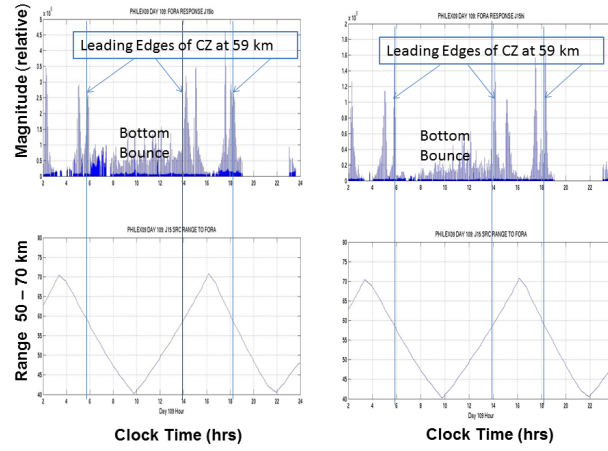


Figure 2: Levels in dB vs. range for low (left) and high (right) compressed LFM signals. Top is the peak picked outputs. Bottom is range. The transmissions start as the FORA crosses away from the 2nd CZ ring at 66 kms on the first star point. Vertical lines are 1st CZ interior edge positions.

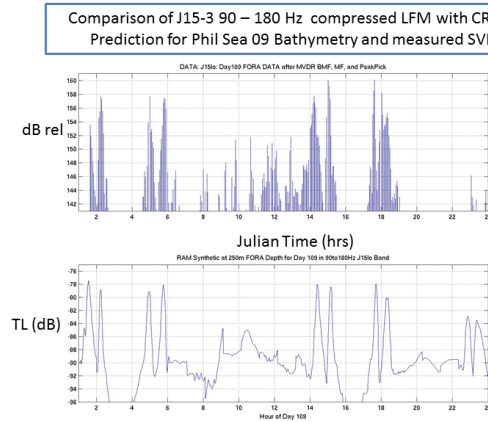


Figure 3: Comparison of experimental low band pulse compressed signal and CRAM prediction. The Julian Time has been mapped to the range as indicated in Figure 2.

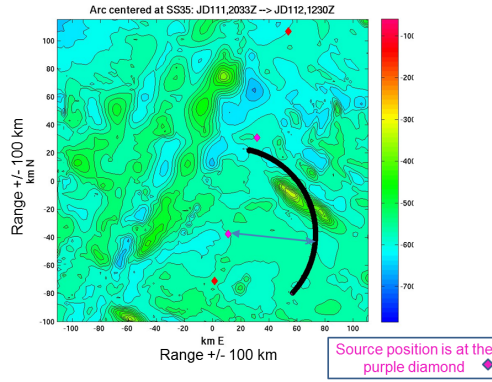


Figure 4: Circular track of the R/V Kilo Moano at constant range of of 59.6 kms from the J15/3 source deployed. The source-receiver separation was maintained to within ± 50 m with the GPS.

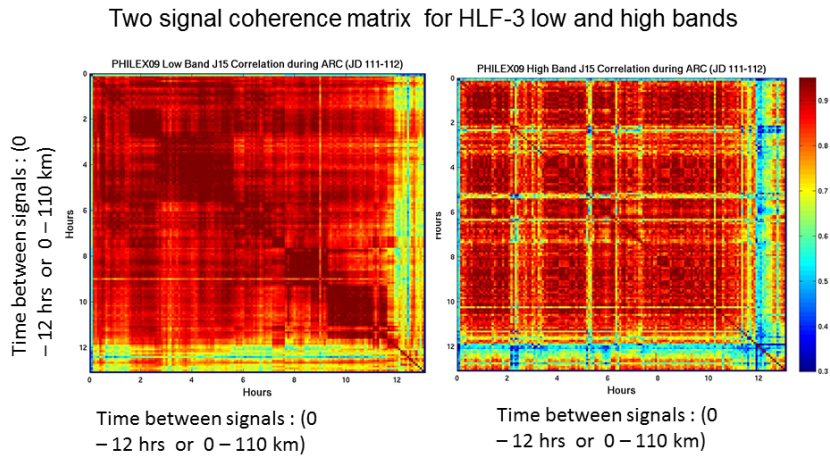


Figure 5: Normalized broadband correlation (coherence) between transmissions for source-receiver separations on a constant range arc. The coherence of the wideband outputs of the pulsed compressed LFM's are measured for up to ≈ 12 hrs or separations ≈ 110 kms cross range.