MODELLING BOTTOM SCATTERING AND TARGET ECHOES FROM DATA COLLECTED DURING THE 2013 TARGET AND REVERBERATION EXPERIMENT

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Abstract: *During the 2013 Target and Reverberation Experiment (TREX13) reverberation and echo data were collected using a fixed source and fixed horizontal array deployed in shallow water in the Gulf of Mexico. Various pulses in the 1.8 to 3.6 kHz band were sent, day and night over a 4-week period, and an extensive analysis of the reverberation data made (J. Yang et al., IEEE J. Oceanic Engineering, TREX13 Special Issue, 2017). Modelling efforts (Ellis et al., IEEE J. Oceanic Engineering, TREX13 Special Issue, 2017) concentrated on analysis of reverberation and estimation of scattering strengths using a range-dependent adiabatic-mode reverberation model. For that work, the bottom scattering assumed a Lambert scattering coefficient. Here, that work is extended to investigate other scattering functions. There is some indication that the reverberation drops off as range (or time) to the* -3.5 *power, intermediate between Lambert's rule and small roughness scattering. In addition, initial estimates are made for the strength of echoes from fixed scattering objects, a towed echo repeater, and the tow ship itself.* [*Work supported by the US Office of Naval Research, Code 322 Ocean Acoustics*]

Keywords: *TREX Experiment, reverberation, target echo, range-dependent modelling, normal modes, energy flux, scattering functions, Gulf of Mexico, towed array*

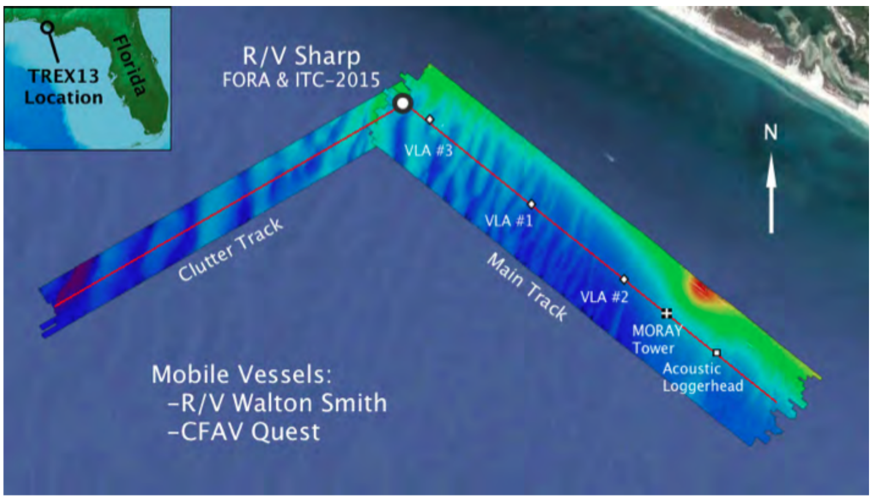
1. INTRODUCTION

TREX was a series of Target and Reverberation Experiments sponsored by the US Office of Naval Research (ONR) in the Gulf of Mexico off Panama City, Florida, USA. Their unique feature was a fixed source and fixed receivers deployed in about 20 m of water, with the acoustic experiments being complemented by an extensive set of environmental measurements to facilitate the understanding of the underlying reverberation and clutter mechanisms, and to support quantitative modelling. The reverberation experiments were primarily organized by the Applied Physics Laboratory at the University of Washington (APL/UW). A preliminary test was conducted in April 2012, with the main experiments conducted 22 April to 16 May 2013. During part of that period Defence Research & Development Canada — Atlantic Research Centre participated along with their Research Vessel *CFAV Quest* and conducted target echo experiments. Extensive environmental measurements were made before, during, and after the main experiment. Results are being collected in special issue of the IEEE Journal of Oceanic Engineering [1].

The main focus was the reverberation experiments, where various pulses in the 1.8 to 3.6 kHz frequency band were sent, day and night for several weeks, and received on a horizontal line array. An extensive analysis of the reverberation data has been made by Yang et al. [2]. Modelling efforts by Ellis et al. [3] concentrated on interpretation of the data, calibration of the matched filter output, and estimation of scattering strengths using a range-dependent adiabatic-mode reverberation model. For that work, the bottom scattering was assumed to be Lambert scattering. Here, that work is extended to handle other scattering functions. In addition, an initial attempt is made to model the strength of echoes of LFM pulses from a towed echo repeater, the tow ship itself, and fixed scattering objects.

2. TREX OVERVIEW

Figure 1 shows the TREX site, and 2013 deployments. The source and FORA triplet array [4] were fixed near the bottom in about 20 m water, moored to research vessel *R/V Sharp*. The data were received on a 48-element array deployed horizontally in a fixed position about 2.1 m from the bottom. Each of the elements were triplets, so the “left-right” ambiguity was resolved, and beams could be formed in the full 360° azimuth [5]. The 0.2-m spacing between the elements made the aliasing frequency about 3.8 kHz for a sound speed of 1525 m/s. At half-wavelength spacing



[Figure from Hefner & Tang, UACE 2014]

Fig. 1: TREX site showing bathymetry and deployments. The ITC-2015 source and FORA horizontal array are fixed near the bottom in about 20 m water. Water depths range from 12 m (red) to 21 m (dark blue). The Main Track is about 7 km and of nearly constant depth; sand dunes are 1–2 m in height, and several hundred meters apart.

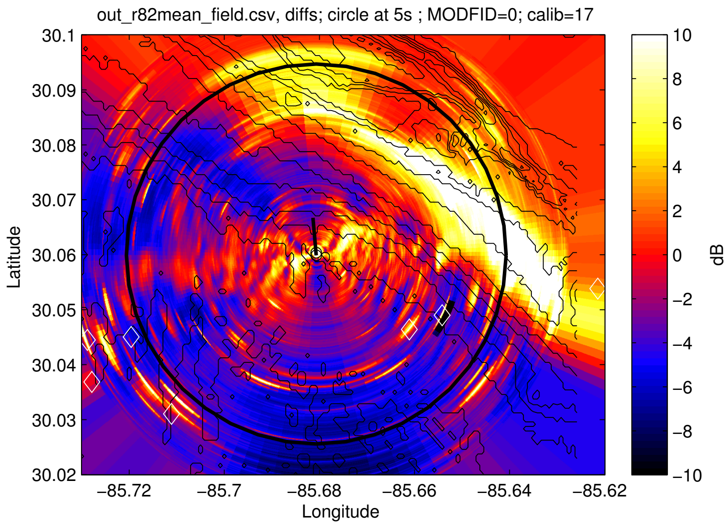


Fig. 2: Polar plot of array beam time series – uncalibrated differences between measured data and Clutter Model prediction, adjusted to be 0 near the array. The circle is at 5 s (3.8 km). A number of scattering objects are evident.

the 48 elements correspond to roughly 96 independent beams, though generally more were used (often 157 beams equally spaced in cosine of the steering angle). The omnidirectional ITC-2015 source, also fixed, was deployed nearby 1.2 m from the bottom. Typical pulses were CWs at 1.9, 2.7, and 3.6 kHz, and LFMs in the bands 1.8–2.7, 2.7–3.6, 1.8–2.0, 2.6–2.8, and 3.4–3.6 kHz. The source levels varied slightly over the band, but were roughly 200 dB re 1μPa at 1 m, and produced reverberation which dropped into the noise after 5 to 10 s depending on conditions.

Figure 2 shows a polar plot of the array beam time series, averaged over $\sim$90 pings, and superimposed on the bathymetry. The data are from a 1.8–2.7 kHz LFM, and differences between the measured reverberation and prediction from the Clutter Model [3] are displayed. The data-model differences have been adjusted to be near 0 dB bear the array. A number of scattering objects show up —some co-incident with known objects— and there are peaks in the reverberation along the Main Track that are correlated with high-resolution bathymetry.

The correlation between the sand waves and reverberation is shown in Fig. 3 which illustrates an implied Lambert scattering strength vs water depth, with the higher scattering coming from the troughs rather than the crests, as models would predict [3] from a uniform scattering strength. This implies some material properties in the troughs, which other researchers are investigating. Here we just concentrate on the lower envelope of the scattering.

2.1. Modelling

For comparisons with data, several models were used. The primary model for the data interpretation was the Clutter Model, which has based on the adiabatic normal modes and can handle bistatic geometry and towed array beam patterns [3]. For more detailed comparisons along a single radial, a simpler monostatic version, R2D3, with omnidirectional source was used. For the latter, the effects of the towed array beam pattern can be approximated by an effective vertical beam pattern [6], which at low angles can be reduced to an effective beam width (EBW) [3]. These models can handle a sound speed profile and layered bottom, but are currently restricted to Lambert's rule for the bottom scattering function. The calculations from Ref. [3] used a bottom half-space with properties obtained from previous experiments in the area: sound speed $c_b = 1680$ m/s, density $\rho_b = 2040$ kg/m^3, and attenuation $\delta_b = 0.84$ dB/wavelength, or 0.5 dB/(m·kHz). There was a slight gradient in the water, but a constant sound speed of 1525 m/s was often used.

To test other bottom scattering functions, some analytical methods [7] were used for a Pekeris

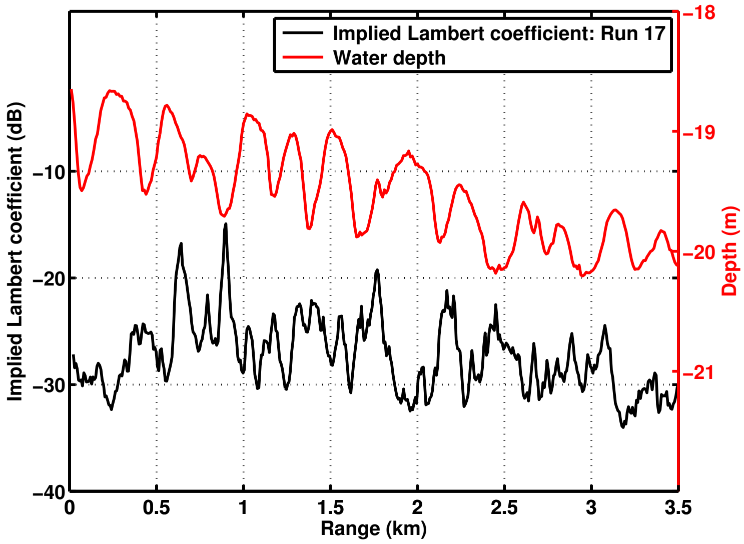


Fig. 3: Implied Lambert scattering strength for 3.4–3.5 kHz LFM along the TREX Main Track compared with bathymetry.

environment, which was quite close to the TREX environment. For scattering functions of the form $S(\theta,\theta') = \mu_b(\sin\theta)^n(\sin\theta')^n$, where the θ are grazing angles and μ_b the strength, Ainslie has developed expressions for range-dependent reverberation [7]. Here, we use the range-independent expressions

$$\frac{R_b}{S_E} = \frac{c_b\mu_b}{8r^{n+2}}\frac{\gamma(\frac{n}{2}+\frac{1}{2},\chi^2)}{H^2(\eta/H)^{n+1}}, \tag{1}$$

where H is the water depth, r the range, $b = 2n$, $\chi = (\eta r/H)^{1/2}\theta_c$, $\eta = \frac{\delta_b}{20\pi\log_{10}e}\frac{\rho_b}{\rho_b}\left(\frac{c_w}{c_b}\right)^2(\sin\theta_c)^3$, and γ is the incomplete Gamma function. For the case of Lambert scattering $n = 1$, the expression simplifies to

$$\frac{R_b}{S_E} = \frac{c_b\mu_2}{8r^3\eta^2}[1-e^{-\chi^2}]. \tag{2}$$

From a TREX13 Workshop (B.T. Hefner, Private communication, Sept. 2016), a strawman environment is $H = 19.6$ m, $c_w = 1525$ m/s, $c_b = 1660$ m/s, $\rho_b/\rho_w = 1.9$, $\delta_b = 0.5c_b$ dB/wavelength from which we get $\eta = 0.791$ and $\theta_c = 23.7°$.

Figure 4 shows reverberation calculated using flux methods for the strawman environment, with different power law scattering functions, compared to measured data from 2.7–3.6 kHz LFMs along the Main Track. The trend of the data seems best fit with $S(\theta,\theta') = \mu_3(\sin\theta)^{3/2}(\sin\theta')^{3/2}$ scattering; i.e., a $\sin^3$ backscattering rule. Note the data begin to drop into the noise at $\sim$7 km (10 s).

3. RESULTS

Previous work concentrated on the reverberation data. Here we wanted to look more at the target echo. Run 82 (JD130 1700–1730Z) seemed a good data set, since it had a low wind speed and significant wave height (Fig. 4 of [8]). The pulses were 1.8–2.7 kHz LFMs with source level of 197.6 dB re 1μPa at 1 m (1μPa^{2}m^2) for duration 0.5 s, and 5% Tukey shading at each end. Accounting for the 0.3 dB reduction due to Tukey shading, that gives a source energy level S_E of 194.3 dB (re 1μPa^{2}m^{2}s). The data were beamformed using Hann windowing and cardioid beamforming of the triplet array [5], and the correlation output was calibrated using the matched filter procedure from the Appendix of Ref. [3].

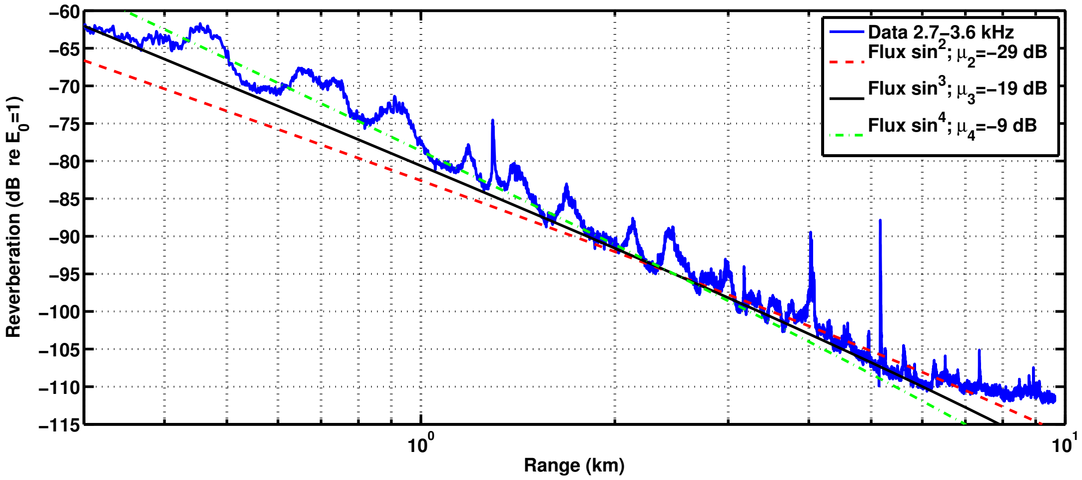


Fig. 4: Measured reverberation data along Main Track normalized to unit energy vs flux comparisons for different scattering rules.

3.1. Reverberation

The time resolution of a 900 Hz bandwidth pulse is roughly 0.0011 s, but there will be time spreading due to multipath propagation and other effects. The matched filter output was sampled at 3125 Hz, but smoothed over 0.0125 s using a 39-point Hann window. It is assumed that this will capture the time spreading, so for the model calculation the pulse is assumed to be of duration 0.0125 s, and have the same energy as the transmitted pulse. The array was pointed in the direction 355°, so the effective reverberation response (compared to an omnidirectional receiver) is -16.19 dB for the beam along the Main Track (bearing 129°), and -17.31 dB along the Clutter Track (bearing 240°).

Figure 5 shows reverberation data along the Clutter Track compared with predictions from a range-independent model and various scattering functions. Though not as clear as for the Main Track the $\sin^3$ backscatter seems to provide a better fit than Lambert scattering, though $\sin^4$ may be better at short times.

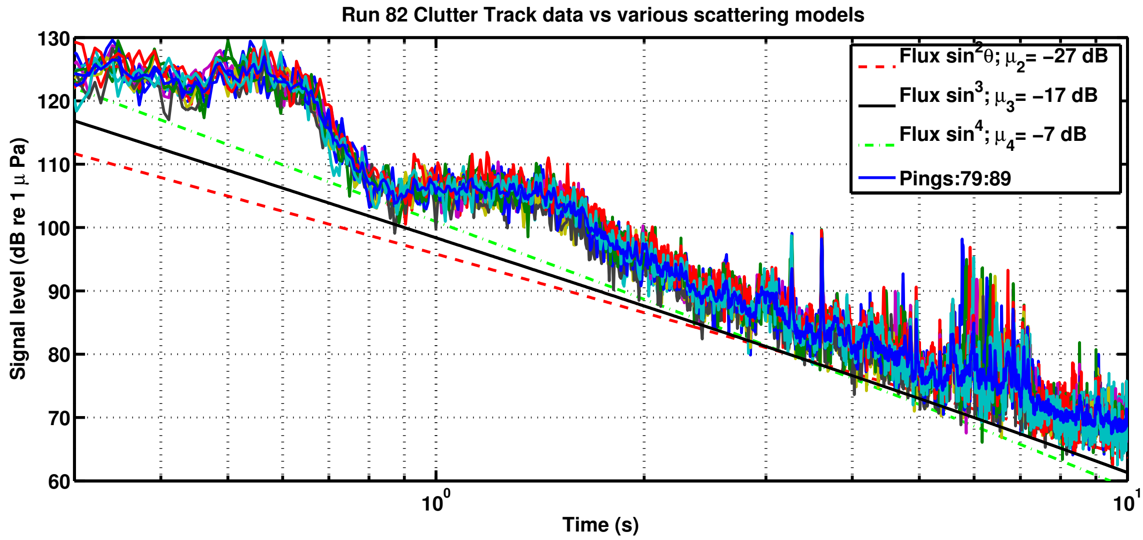


Fig. 5: Some fits to reverberation along the Clutter Track using various scattering functions.

3.2. Target echo

A number of data sets were taken with *Quest* towing an echo repeater along the Main and Clutter Tracks. The echo repeater consisted of a source towed immediately behind *Quest* at a depth of approximately 9 m, and a 16-channel array towed about 70 m behind *Quest* at depths of 5–10 m to receive the direct transmissions from ITC source. The received signal from one hydrophone was used as a replica for the echo repeater. Figure 6 illustrates the received signal on FORA Beam 101 (244° clockwise from forward endfire) during the first half hour of Run 82 with *Quest* towing the echo repeater outward on the Clutter Track. The echo repeater was in "ping-pong" mode; that is, each signal was transmitted twice. On the first transmission the echo repeater recorded and saved the received signal; the second transmission was preceded by a trigger pulse, which then caused the echo-repeater to transmit the signal stored from the previous pulse. For this run the echo strength was set to 0 dB. To avoid interference with the echo from the hull of *Quest* a delay of 0.3 s was incorporated. The start times of each ping are aligned, so the track of *Quest* and the echo repeater can be seen on the plot. The echo from *Quest* can be seen on every ping, and the echo repeater response (delayed 0.3 s) on every second ping. The vertical lines in the plot represent static clutter objects in the beam. Moving scattering objects can be seen in the beam, generally drifting toward FORA.

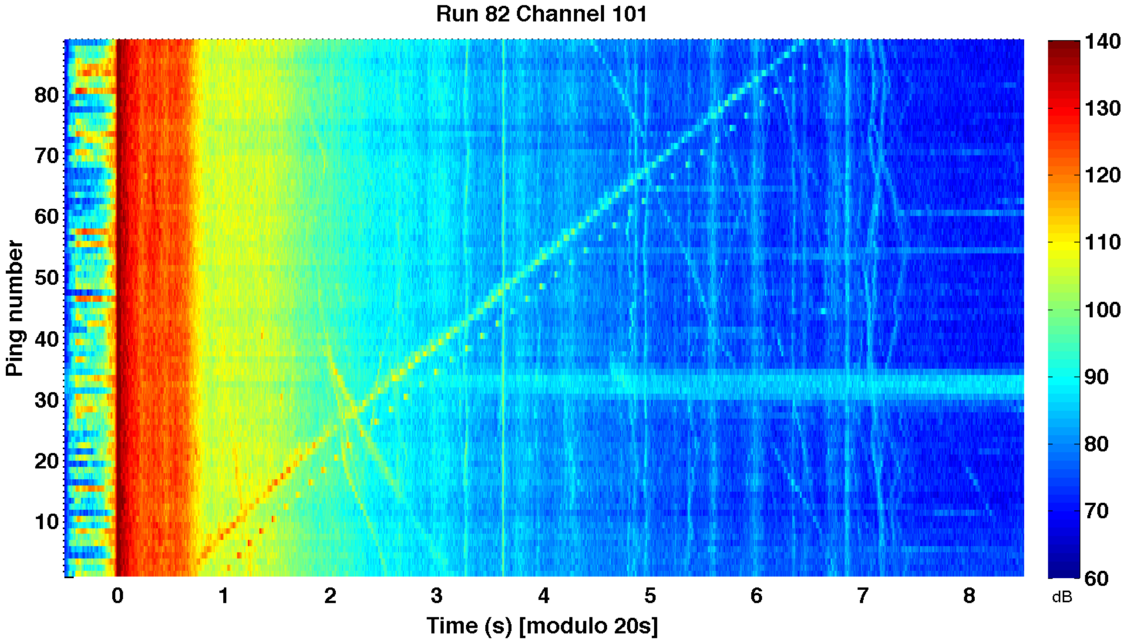


Fig. 6: Echo-repeater run on Clutter Track.

Figure 7 shows a line plot of the echos on the Clutter Track for the odd pings – no echo repeats. The echos will be from the stern of *Quest*. The model calculation used a slightly downward refracting profile corresponding to a CTD at the end of the Clutter Track [8, Fig. 2]. The calculation used the strawman bottom halfspace, the range-dependent reverberation model, bathymetry along the Clutter Track, Lambert rule for bottom scattering with $\mu_2 = -29$ dB, and a 0 dB point target at depth of 5 m. The downward refracting profile reduces the target echo about 2 dB compared to an isospeed profile, which was used for the Main Track; the profile causes minimal effect on the bottom reverberation.

Figure 8 shows an enlarged portion of 6 pings near range 3.5 km arriving 4.5–4.9 s, with echo repeats from the even pings delayed 0.3 s. There is some indication of a pre-arrival before the echos from the hull. The echo repeats are close to the predicted value for a 0 dB target. The echos from the *Quest* hull are slightly higher; together with the more complete set of echos in Fig. 7 a *Quest* target strength of $\sim$5 dB or less is implied.

Figure 9 shows the received signal from 89 pings from Run 82 on a vertical line array (VLA1) at range 2.4 km and the 15-m vertical air hose (PAT) at range 2.75 km. The PAT echo is stronger and more compressed. The VLA echo is spread out more in time, and more variable. Estimates for average received level are: 112 dB for the PAT and 105 dB for the VLA. Using the upper echo curve from Fig. 7, their estimated target strengths are 10 dB and 0 dB respectively. A

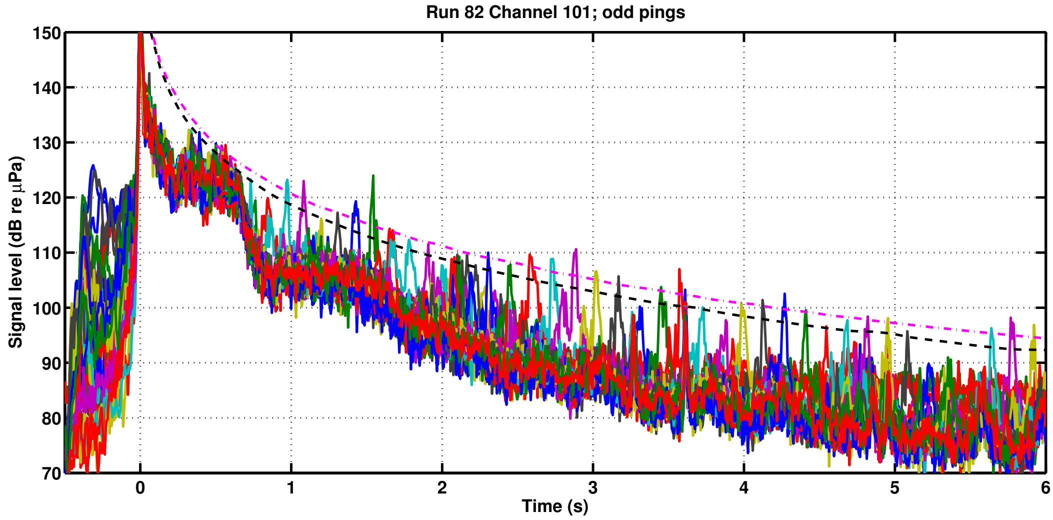


Fig. 7: Received signal for odd pings on Clutter Track for Run 82. The dashed black line is a echo calculation for a 0 dB point target at 5 m depth. The magenta dash-dot line is an echo calculation for a 0 dB point target at depth 10 m along the Main Track.

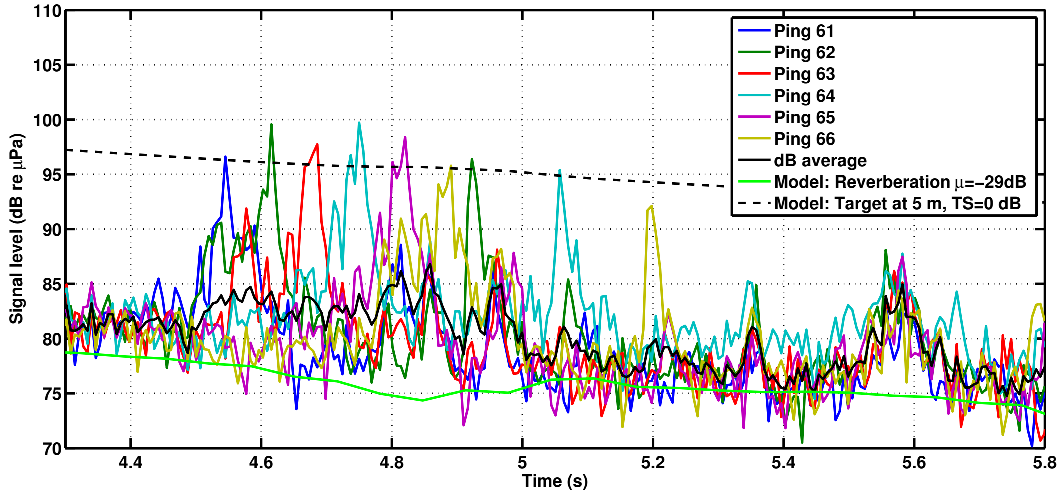


Fig. 8: Six pings, near range 3.6 km, showing echo repeat delayed 0.3 s on the even pings.

similar vertical array VLA2 (at range 4.2 km) has received levels roughly 98 dB, and estimated target strength of 2 dB. These target strengths are of course approximate, being dependent on the estimated transmission loss.

4. SUMMARY

Initial estimates of the bottom Lambert scattering strength were made in Ref. [3]. Here, additional model-data comparisons have been made for TREX reverberation and target echo data. There seems to be some indication that the reverberation fits a $\sin^3\theta$ backscattering law which gives a $r^{-3.5}$ range dependence. This is midway between the commonly used $\sin^2\theta$ of Lambert's rule, and the low-angle $\sin^4\theta$ given by perturbation theory. It is possible that volume scattering from the subbottom is making a contribution.

The reverberation predictions are relatively independent of the sound speed profile, but the near-surface target echo is somewhat affected by it. Thus, the target echo is less well determined. Initial estimates are that the echo from the hull of *Quest* is $\sim$5 dB or less, the 15 m vertical hose (PAT) is about 10 dB, and the Scripps vertical array is about 0 dB. Other runs, additional analysis, and better transmission loss estimates are required to refine these estimates.

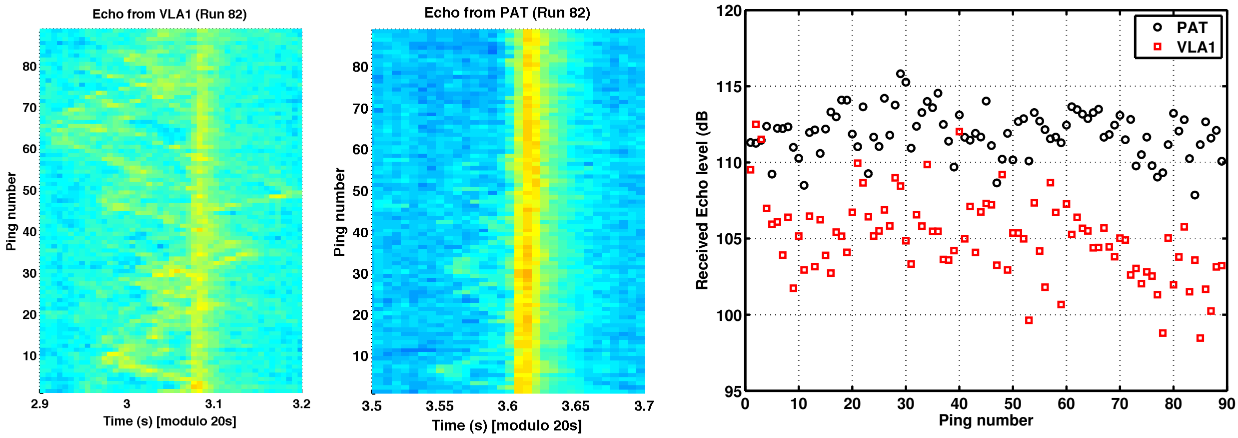


Fig. 9: Left and middle: Received signal levels for VLA1 and PAT using the same colour scale as Fig. 6. Right: A more quantitative plot showing peak level and ping-to-ping variability.

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