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Verification and Validation Study for Extraction of Ocean Bottom Acoustic Backscattering Strengths

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14. ABSTRACT Researchers from the Naval Research Laboratory (NRL) and the Applied Research Laboratories: University of Texas (ARL:UT) collaborated on a verification and validation study for a “through-the-sensor” methodology of extracting bottom scattering strengths from the AN/SQS-53C sonar. The primary goal was to establish the capabilities for the methodology, Sonar Bottom Active Boundary Loss Estimation (SABLE), in the area of characterizing acoustic interactions with ocean boundaries for exercises involving this sonar. SABLE features include the capability to obtain georeferenced maps of acoustic information (i.e., collecting information within latitude/longitude grid cells). NRL investigations established the validity of the SABLE approach to bottom backscattering computation and checked the accuracy of the results by performing independent processing of received acoustic time series. The comparisons indicated that differences in scattering strength in SABLE and NRL processing for the selected ping set were on the order of 1-2 dB. [Work supported by SPAWAR PMW-120.]					
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VERIFICATION AND VALIDATION STUDY FOR EXTRACTION OF OCEAN BOTTOM ACOUSTIC BACKSCATTERING STRENGTHS

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1 INTRODUCTION

In 2007, researchers from the Naval Research Laboratory (NRL) and the Applied Research Laboratories: University of Texas (ARL:UT) collaborated on an effort to perform a verification and validation (V+V) study that would establish the viability and accuracy of the SABLE (Sonar Active Boundary Loss Estimation) “through-the-sensor” methodology [1] for extracting georeferenced (computed for a set of latitude/longitude grid cells) bottom backscatter information from AN/SQS-53C transmissions. The capability to produce accurate measurements of bottom backscattering parameters in areas of operational interest, especially where existing experimental or fleet exercise data are available, was identified as a goal of the PMW-120 Ocean Bottom Characterization Initiative (OBCI) project. The bottom backscattering maps that are planned for development under the OBCI project are intended for use by tactical decision aids in modeling the performance of mid-frequency sonar systems.

The first part of this report summarizes the general methodology and capabilities of the SABLE processing system, briefly describing how SABLE selects and databases the appropriate information for direct-path interactions with the ocean bottom, and how a bottom backscatter map, as a specific example of a SABLE-derived product, is extracted. The intention is to place the V+V study of bottom backscatter extraction in context, and to discuss other possible uses of SABLE, such as the extraction of bottom loss.

The second part of the report describes the independent analysis of the same AN/SQS-53C data by NRL and ARL:UT. Earlier V+V efforts, focusing on NRL examination of SABLE code and ARL:UT reverberation modeling with SABLE-derived bottom backscattering parameters, are also described. The results of the new V+V effort are presented in the form of a detailed term-by-term sonar equation comparison of NRL and SABLE processing of the computed backscattering of bottom scattering strengths. A brief description of the possible impact of biologies is also provided. The report concludes with NRL recommendations for future SABLE processing, and a conclusion regarding the role of SABLE in future efforts.

2 MID-FREQUENCY THROUGH-THE-SENSOR CAPABILITIES

2.1 SABLE Databases and Bottom Backscatter Extraction

SABLE is a processing system for extracting/retaining georeferenced environmental information from AN/SQS-53C transmissions, and was developed at the Naval Oceanographic Office and ARL:UT by Drs. Gene Brown and Marti Barlett (both currently with ARL:UT). As a system for remote sensing of acoustic parameters, it uses the directionality, waveform resolution, and the sonar setting flexibility of the system

advantageously to obtain measurements with the spatial resolution required for modeling reverberation in realistic range-dependent environments. For scattering strength measurements, it considers the most basic ray paths (in the case of bottom scattering, acoustic ray paths involving only one interaction with the bottom) and does not make recourse to geoacoustic inversion of complex, layered bottoms. As a system that does not rely on specific sonar settings, waveforms, or ship tracks, it can be used on existing and future exercises for which it is not desirable to modify platform tracks or sonar settings to obtain environmental acoustic information - i.e. it operates on a “not-to-interfere” basis. The “kernel” of SABLE is the ability to use raytracing and beampattern information to calculate the latitude/longitude cell (or “grid cell”) of the acoustic interactions with the ocean bottom that are appropriate for databasing. Another important feature is the interactive nature of the SABLE database and SABLE-derived products. For example, a SABLE-derived product such as a bottom backscatter map allows a user (using simple MATLAB commands) to visualize georeferenced maps for specific data subsets such as a particular depression/elevation angle or time of day. (The latter allows for the possible identification of fish scattering effects). For bottom scatter and bottom loss maps created to date, latitude/longitude cells have been squares with sides on the order of hundreds of meters. A more detailed description of the methodology for SABLE analysis of acoustic time series is given in [1]. A demonstration of the methodology for creating a SABLE-derived product is given in Figure 1.

SABLE computes a variety of statistics, including the mean reverberation, for selected time intervals (or “discrete measurements”, as described in [1]). These statistics include the moments, travel time to grid cell, threshold crossings, etc. For the example shown in Figure 1, a particular statistic, the mean reverberation, has been extracted from the SABLE database to perform bottom backscatter and loss calculations. To be included in the georeferenced map of bottom backscatter or bottom loss, the results from a discrete measurement must meet a set of criteria for being direct-path interactions with the ocean bottom that are free from ambiguous returns resulting from ray paths that include a surface reflection and/or multiple bottom interactions. The resulting areas for which SABLE computed statistics that met these criteria are the white areas in the left plot of Figure 1. The selected size of a grid cell depends on the distribution of valid discrete measurements in these areas. The extracted information within each cell populates a SABLE database, and can be used to produce a SABLE-derived product for a desired statistic. To produce the bottom backscattering map shown here (the right plot of Figure 1), a Lambert coefficient is computed for each by estimating a Lambert coefficient (μ) for the data obtained for multiple acoustic interactions within a grid cell (the number of which can be augmented as the number of pings increases). These values are estimated from Lambert’s law for the case of monostatic backscatter

$$BSS = \mu + 10 \log(\sin^2(\theta))$$

where BSS is the bottom backscattering strength in decibels and θ is the grazing angle. (In this report, we refer to a single grazing angle for pure backscattering, with a co-located source and receiver). The multiple μ values within a grid cell are averaged to produce a single μ value for the cell. To address the issue of gaps in coverage, a

combination of depth and spatial interpolation of μ values has been used to create the right plot of Figure 1.

It should be stated that a Lambert coefficient map is only an example of a SABLE output for acoustic backscatter. The reverberation statistics can be used to create other representations of the bottom scattering, including alternative assumptions of dependence on grazing angle. The Lambert's coefficient map is designed for use by the Navy standard model used for predicting mid-frequency sonar performance.

2.2 Assessment of Current SABLE Capabilities

SABLE's methodology for obtaining bottom loss as a function of grazing angle uses paths that include two bottom interactions, as described in [1]. While bottom loss calculations are outside the scope of this report, the general statement can be made that further investigation is needed to determine whether the grazing angle coverage of this approach will be sufficient for robust estimates of bottom loss. The potential for geoacoustic inversion of the parameters (speed, attenuation, roughness) of the water/bottom interface and near-interface is another area that can be explored. Given the frequency band of the sonar and the limited penetration of these signals into the sediment, these inversions are not the most direct way to populate geoacoustic databases such as GABIM, which include the layering structure and are intended to be used by low-frequency systems as well. Given that scattering strength can strongly depend on system geometry and transmit frequency, the SABLE results (e.g. Lambert coefficients) produced from analysis of AN/SQS-53C data do not necessarily apply to other systems.

From an operational standpoint, SABLE provides a means of obtaining future data sets on a "not-to-interfere" basis, as it uses standard AN/SQS-53C sonar modes, does not require specific tracks, waveforms, or sonar settings, and uses information from multiple depression/elevation angles to enhance coverage. The project has also developed a hardware capability for tapping into the data stream (with a view to near real-time processing), but for this report, we are focused on its off-line processing capability. ARL:UT researchers have stated that data sets collected by the AN/SQS-53C within the last 5 years generally contain the necessary non-acoustic information for the creation of a SABLE database.

SABLE processing of bottom backscatter has been performed in water depths from 75 to 2000 m. The V+V study described in this report uses data with a water depth of 1300 m. From a practical standpoint, shallow water areas may include complex bathymetry that can produce ambiguous returns (due to beam sidelobes and/or multipath) from prominent bathymetric features. This is not an issue for the area under discussion in this paper, but has been raised as an issue with SABLE measurements in an area off the southern California coast [2]. Future development of the SABLE code will address this issue through modifications to the data processing.

Although the data sets already in the possession of ARL:UT may meet short- to mid-term OBCI requirements, issues relating to future data acquisition are still relevant. As SABLE is not a survey methodology, it does not require the platform to run a specific type of track, it has been of interest to make rough estimates of the geographical coverage of a SABLE bottom scatter map as a function of data acquisition time. As the rate of

coverage depends on the redundancy of the ship track and the oceanographic conditions, the estimates we obtain can be considered to be “order-of-magnitude” calculations. We have made three such estimates for the bottom backscatter map coverage (in English units for convenience):

- 1) For a platform traveling at 10 knots in a straight line, the “swath” of SABLE coverage can be taken to be 1 nmi (shallowest water), 3 nmi (lower bound), or 15 nmi (reasonable upper bound) on each side of the ship. If we use a value of 10 nmi, the coverage estimate is 100 sq nmi/hr (343 km²/hr).
- 2) For a SABLE backscatter map collected off the southern California coast, the coverage estimate is 50 sq nmi/hr (171 km²/hr).
- 3) For the area of interest for this report, the coverage estimate is 40 sq nmi/hr (137 km²/hr).

3 NRL/ARL:UT VERIFICATION AND VALIDATION EFFORT

3.1 Verification and Validation Methodology

NRL has taken an interest in SABLE development over the past several years. Dr. Fred Erskine, having developed various modules of the NRL scattering strength processing software in the 1980’s, reviewed SABLE algorithms by inspecting parts of the SABLE code. In 2006, Drs. Erskine and Brown collaborated on a study of the preliminary Lambert coefficient map of Figure 1 and presented CASS reverberation modeling results using the values in various cells. With the exception of a specific, relatively small area for which the Lambert’s coefficients were anomalously low, the SABLE-derived Lambert coefficients provided accurate modeling for the reverberation level associated with the first bottom interaction. In 2007, NRL requested a specific V+V effort focusing on independent processing by NRL and ARL:UT, involving further review and recommendations by the author of this report. This involved validation that the SABLE algorithms were appropriate for the task at hand, and verification that the SABLE values for scattering strength, and the individual terms used to compute scattering strength, could be produced independently by NRL’s scattering strength processing system.

NRL has a history of performing bottom backscatter extraction going back to the 1980’s. NRL efforts, documented in NRL reports and journal articles, focused on low- and mid- frequency backscatter (70 Hz-10 kHz) in the Active Adjust Undersea Surveillance project, the Critical Sea Test program, the T-MAST program, and the Littoral Warfare Advanced Development project [3-6]. In these investigations, NRL has used explosive (SUS), vertical line array, omnidirectional or dipole sources that were deployed with horizontal or vertical line arrays as receivers. Additionally, NRL processed AN/SQS-53C data from the Eastern Mediterranean and obtained scattering strengths that were consistent with values obtained by Hanrahan of Planning Systems Incorporated and featured significantly greater coverage in grazing angle [7].

NRL and SABLE processing both involve a sonar equation plane-wave computation, which can be written in units of decibels as follows:

$$\text{BSS} = \text{RL} - \text{SL} + \text{TLs} + \text{TLr} - 10 \log A$$

where BSS is the bottom scattering strength, RL is the reverberation level, TLs and TLr are the transmission losses from the source to bottom and bottom to receiver, respectively, and A is the ensonified area.

We now consider issues relating to the individual terms:

Reverberation level (RL): NRL and SABLE both compute reverberation levels over successive intervals of a bandpass-filtered and decimated version of the received time series. In the general case, an appropriate time interval is selected for computation of the mean reverberation level and the raytrace information is used to assign the center of the interval to a specific grazing angle of acoustic interaction with a locally flat ocean bottom. In this case, the time interval was taken to be equal to the duration of the transmitted signal. As stated above, SABLE rejects some of these discrete measurements when creating derived products so that ambiguous returns do not affect the computation. The starting time for succeeding time intervals advances by a selected value, which may result in an overlap between successive time intervals. In the results shown here, the start times of the time intervals differed by the ping duration, so that each computation of the reverberation level contains independent time series data (no overlap).

NRL and ARL:UT discussed the appropriate calibrations with the developers of the AN/SQS-53C sonar during the 2006 analysis efforts of Drs. Erskine and Brown. The calibrations depend on waveform and sonar operating mode (the differences in calibration values due to depression/elevation angle are on the order of tenths of a degree).

After agreeing on the time interval size/overlap and system calibrations, NRL and ARL:UT proceeded to compute reverberation levels. Two differences in the processing methodology are notable. The first is the NRL method for computing reverberation level by Fourier transforming the segment of reverberation data in the time interval and computing the area under the resulting power spectrum. This approach arises from the historical NRL method of obtaining bottom scatter with SUS, for which outlying observations in scattering strength could be traced to irregularities in the spectrum of the returned signal. For some NRL experiments, frequency-domain observation has allowed the analyst to observe any contaminating signals (e.g. ship noise lines) that could affect the results. SABLE computes reverberation level by computing a mean level directly from the time series. Since AN/SQS-53C data observed by NRL in this experiment and the SHAREM 137 experiment did not exhibit any irregularities in the spectra, we did not see a reason to modify the SABLE approach.

The second difference in the computation of reverberation level involves the case where significant reverberation decay occurs over the span of a time interval. NRL uses a “slope correction” [3] for parts of the time series where the level is changing rapidly and the assignment of the reverberation level to the center of the processing window, given a rapid decent in the slope over the time interval used for processing, leads to an overestimation of the scattering strength. NRL has recommended that this computation be

performed in future SABLE data processing. For the example shown in this report, the slope correction was greater than 1 dB for a very small subset of data points.

Transmission loss (TL): NRL and ARL:UT use different models for transmission loss. NRL uses raytrace code written in the 1980's by R. Pitre [8], while SABLE uses the raytracing capability provided by the Comprehensive Acoustic Simulation System (CASS). The models not only predict transmission loss, but also the horizontal range of the eigenrays from the source/receiver location for to the bottom. NRL has used models for water column mineral absorption and computed an additional transmission loss using only the horizontal range to the bottom interaction [7]. SABLE is capable of computing its own absorption coefficients for ray paths. As the SABLE estimates are based on actual ray path lengths, we considered the SABLE treatment to be superior. In the case shown in this report, mineral absorption was on the order of 1 dB in the most extreme case, and we decided to omit absorption from the calculations rather than compare the NRL and SABLE results.

NRL and ARL:UT considered source and receiver beam pattern estimates from three different sources of information. It was found that since only the characteristics of the main lobe were relevant to the scattering strength extraction, all of the beam patterns that were considered would have been adequate. In the transmission loss computations presented below, beam pattern effects are insignificant because the comparison was confined to the main axis region (beam response within 1 dB of peak).

Ensonified Area (A): SABLE and NRL both compute the ensonified area for a particular time interval. The horizontal beam pattern is handled in the same manner for both processing systems, using the value of 11 degrees for the horizontal beamwidth.

3.2 Verification and Validation Results

Figure 2 shows the region of acoustic direct-path interactions with the bottom for the 45 pings used in the V+V effort. As the NRL processing system assumes a flat bottom, comparisons were made for an area with a relatively constant water depth, and the effect of assuming different water depths (within the range 1100-1400 m) on the scattering strength level was investigated and found to be small (< 2 dB). While SABLE is capable of using bathymetric information to calculate the grazing angle relative to a local slope, it was run with a flat bottom assumption for the purposes of this comparison. For the plots below, a subset of 15 pings (HFM transmissions) with the D/E angle of 5 deg down was used, as the other D/E angles added very little additional grazing angle coverage to the scattering strength curves, due to the strong downward reflecting nature of the sound speed profile.

Figure 3 shows the resulting scattering strengths for the SABLE and the NRL processing system. The upper left plot is a typical result for a single beam and single ping. The vast majority of plots of individual pings and beams have differences in level on the order of 1 dB. The average over pings for a typical beam in the lower left plot shows more clearly that the SABLE scattering strength is generally higher by about 1-2 dB. (The averaging is performed after conversion of the scattering strength to decibel

units.) The upper right plot shows results for multiple beams for a single ping (the multiple beams giving “stacks” of data points at various grazing angles). Note that the SABLE data are offset in grazing angle, as seen by the alternating columns of “red” and “blue” data. This is a result of the different ray tracing programs used by NRL and SABLE. Note that the range of scattering strength values is similar for similar grazing angles, i.e. the variability across horizontal beams (azimuth) is similar. The lower right plot contains data from a single beam for multiple pings, which has the same offsets in range as the upper right plot. The range of scattering strength values is similar, but in this case, it represents a comparable variability over time.

For the same set of pings, we investigated the computations of the terms in the sonar equation given above. The 2-way TL (TLs + TLr) is given in the left plot of Figure 4. Note that the NRL system predicts a smaller transmission loss over the entire range of valid data. As this difference is only about 1 dB for each way, we did not investigate further into the differences in computed TL. The ensonified area calculations are shown in the right plot of Figure 4. Allowing for the offsets in range, the ensonified areas are within tenths of dB.

NRL also processed CW’s as well as HFM transmissions, and no dependence on the scattering strength on waveform was observed. SABLE currently processes the HFM pulses only, but the required modifications for CW processing are straightforward.

3.3 Assessment of Biological Impact

The presence of biological scatters near the ocean bottom can affect scattering strength measurements and produce a false value for the Lambert coefficient. An example of rockfish affecting a bottom scattering strength measurement over a mudstone ocean bottom is given in Gauss [6]. For the general geographical area (including Figure 1), the lead author commissioned an analysis of the fish scattering behavior in the area of interest [9], deriving provinces of varying fish behavior and predicting scattering strengths based on historical measurements and a physics-based swimbladder scattering model for extrapolating scattering strengths to different frequencies. The results pertaining to the V+V work were as follows:

- Daytime fish impact is negligible (layer scattering strengths below -50 dB).
- Nighttime fish did not affect the results in the grazing angle band used to obtain bottom scattering strength. They could have an effect if the measurements are performed in shallower water at lower grazing angles.

The most direct method of assessing biological impact on a SABLE database is to compare day and night results (since day/night scattering strengths from the types of fish of interest are generally different). In cases where the day and night results are not in the same area with the same sonar settings, an assessment of the type performed by Nero needs to be performed if historical data provide any indication that fish produce significant scattering strength in the AN/SQS-53C band.

4 SUMMARY AND RECOMMENDATIONS

NRL V+V efforts have established the ability of SABLE to produce a specific derived product to meet goals of the OBCI project, verifying SABLE's basic methodology of performing analysis of direct-path returns and extracting scattering strengths by calculating terms in the sonar equation for a sequence of time intervals, with the proper controls in place to omit measurements that are the results of ambiguous ray paths. SABLE is an efficient means of extracting bottom scatter georeferenced maps from existing ARL:UT holdings, and should generally produce good results with high coverage rates for future data acquisition. NRL and ARL:UT successfully collaborated on a methodology for direct comparison of results based on the terms of the sonar equation, and ARL:UT's efforts in extracting the desired processing outputs to conform with NRL characterizations of the acoustic environment were instrumental in making the comparison. The differences in scattering strength arise primarily from a difference in the estimated transmission loss, but falls within the range that was taken to constitute agreement in the V+V proposal (< 2 dB difference).

NRL has recommended some modifications to SABLE that could increase robustness of the Lambert coefficient estimates. Specifically, it should lead to more consistent results if scattering curves from different D/E angles within a cell are combined and the best Lambert coefficient (based on fitting a Lambert's law model or some other assumed model) is obtained from the widest possible range of grazing angles. Additionally, NRL recommended that SABLE consider the inclusion of returns for which there is a surface bounce path comparable to the direct-path, where a 3 dB correction should suffice. The inclusion of pings containing these paths (currently discarded by SABLE) could help to augment the overall amount of data used to compute the Lambert coefficients.

NRL has also discussed with SABLE developers issues relating to the use of SABLE backscattering maps from performance modeling. One issue is whether to correct for changes in local bottom slope (within the grid cells of the bathymetry used to calculate eigenray interactions with the bottom). A second issue is the use of the backscattering map for different AN/SQS-53C waveforms – while SABLE information can be separated into different backscatter maps depending on the transmitted waveform, the exact waveform to be used in system performance modeling may have sparse or non-existent data. In that case, the user must be provided with a means of obtaining information for the most closely related available waveforms.

The investigation of biological scattering, in addition to its function in validating SABLE results in this particular area, should be of general interest to researchers involved in performance predictions in this area. The report, which is limited to DoD or DoD contractors, explicitly gives the longitude/latitude box of interest.

It is also recommended that V+V efforts on future SABLE databases be performed, including an assessment of biologic impact, the use of reverberation models to assess possible ambiguous returns from bathymetric effects, a study of the effects of

performing the analysis in shallow water (if applicable), and a sonar equation comparison using the methodology that was developed under the current effort.

5 ACKNOWLEDGEMENT

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9. Inquires about this reference should be made to Raymond Soukup (raymond.soukup@nrl.navy.mil). The distribution of this reference is limited to DoD and DoD contractors only.

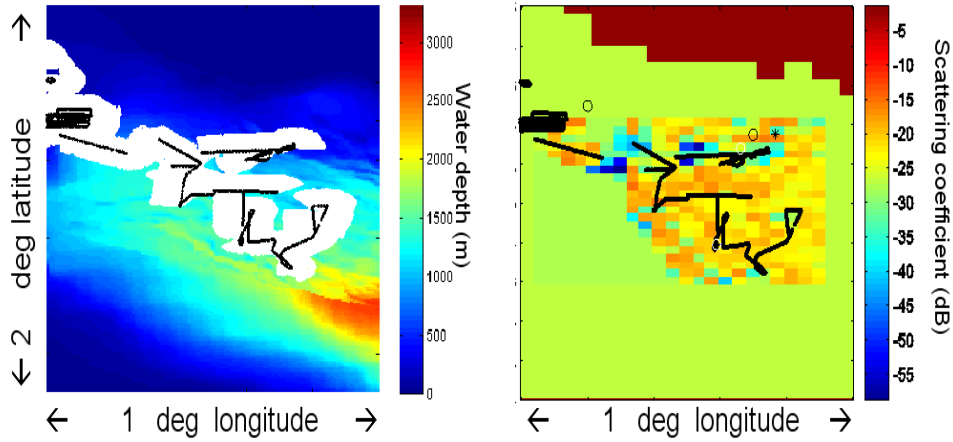


Fig 1: Left: AN/SQS-53C track with SABLE-determined areas (in white) for bottom scattering extraction. Right: Example SABLE product – Preliminary Lambert's coefficient database.

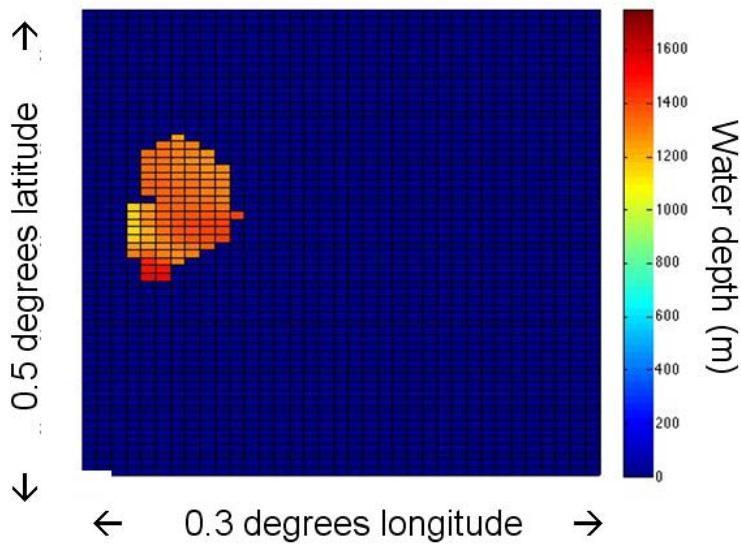


Figure 2: Region of direct-path interactions with the bottom with the subset of pings used for the V+V comparison of SABLE and NRL processing. (All blue pixels represent the region without unambiguous direct-path bottom interactions, which were assigned a water depth of 0 for display purposes.)

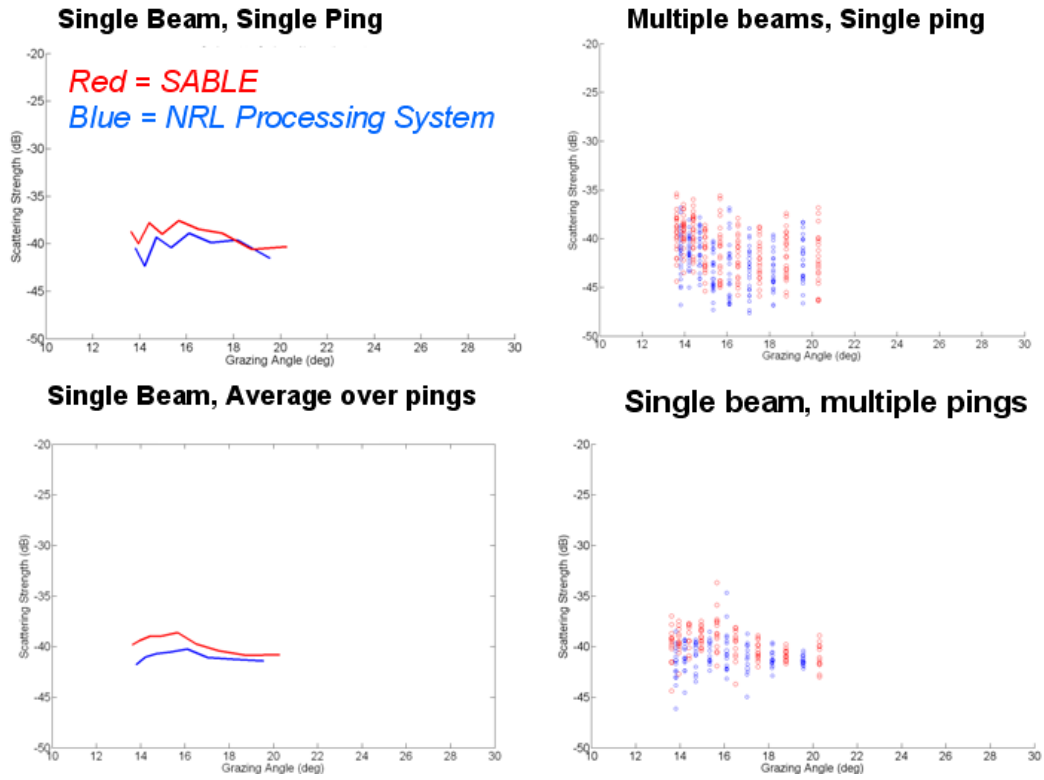


Figure 3: Comparison of scattering strength results from SABLE (red) and the NRL Processing System (blue). Upper left: Typical result for a single horizontal beam, single ping. Lower left: Single beam, average scattering strength over ping set. Upper right: Results for multiple beams, single ping. Lower right: Results for a single beam, multiple pings.

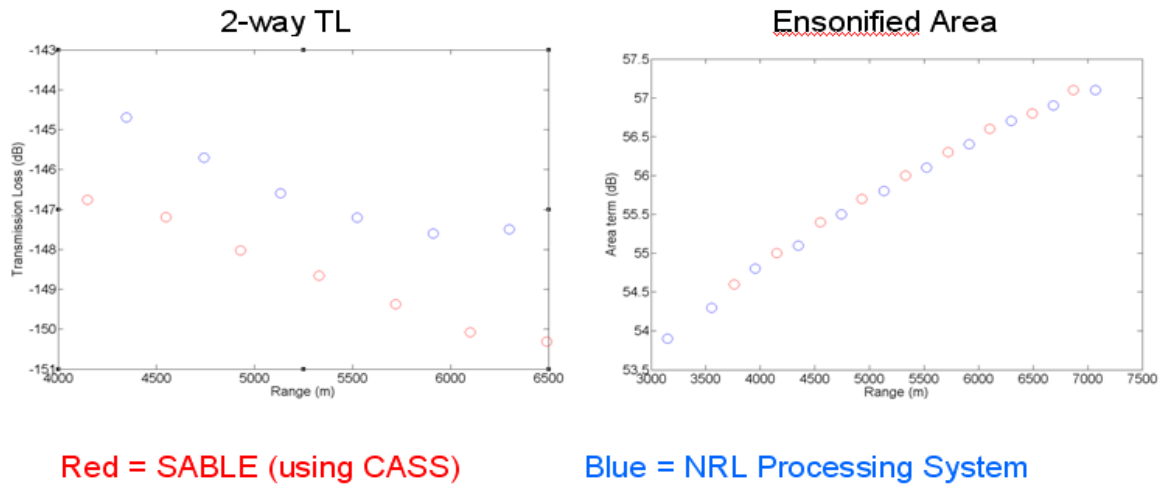


Figure 4: Comparison of sonar equation in the scattering strength computation for SABLE (red) and the NRL processing system (blue). Left: 2-way transmission loss. Right: Ensonified area