Calibration Schema for a Long-Range, Fishery-Research Side Scan Sonar

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Abstract--The NOAA National Marine Fisheries Service owns two Long-Range, Fishery-Research Side Scan Sonars (Klein model 7180). Having recognized a number of serious shortcomings in the original design and implementation of the 7180, NOAA embarked on an upgrade of the 7180 to bring the 7180's performance closer to the requirements of fish-habitat researchers for radiometrically adjusted backscatter observations from a calibrated sonar. With three-meter long mechanically curved arrays, it is difficult / impractical to calibrate the 7180 side scan sonar using conventional methods. However, given the recognized importance of calibrated and radiometrically adjusted backscatter data for fishery research, a schema was developed for the 7180 that built on, and extended, the protocol for calibration of multibeam sonar [1]. This paper describes the cascade calibration schema and presents results from applying it to the upgraded 7180 during a recent survey in the eastern Bering Sea. With this method, it is now possible to trace the 7180 backscatter levels to a recognized standard and to detect the onset of discrepancies among the several spatially overlapping measures of backscatter. This advances the fishery-research goal of consistent seabed characterization across wide swaths of the seabed.

Keywords—calibration, source level, backscatter, fish habitat, side scan sonar

I. INTRODUCTION

Current research in fisheries science is developing basin-scale quantitative models that are intended to identify essential fish habitats and promote sustainable harvests from commercially important marine fish populations [2]. Many of those fish dwell on, or near, the seabed and have strong affinities for certain sediment types [3]. In those cases, radiometrically adjusted backscatter measurements from a calibrated sonar could be useful inputs to habitat models, as well as, provide quantitative information about seabed characteristics that is obtained much more efficiently than with direct sampling methods.

I A: Sonar System Upgrade

The 7180 was designed and built before it was recognized that the seafloor backscatter angular response function between nadir and 40 degrees off-nadir contains a preponderance of the information that can be usefully employed in the inference of seabed sediment properties from acoustic backscatter. In other words, the 7180 design predated the publication describing GEOCODER processing [4]. In the initial design of the 7180, the "nadir gap" was filled with backscatter measurements made at a constant off-nadir angle of 40 degrees, consequently their contribution to the inversion of the backscatter angular response functions to yield sediment grain size, was limited. The original 7180 design provided 1000 m wide, continuous port-to-starboard coverage of backscatter data however those data were not functionally fit for the intended fishery research. Consequently, NOAA made the decision to upgrade the 7180.

The upgrade of the 7180 was constrained to make maximum utilization of the system's original hardware and software. As part of the 7180's upgrade, the previous scheme of using just frequency and pulse diversity to isolate the several subsystems was changed to a scheme of using time, frequency and pulse diversity. The 7180's original nadir augmentation subsystem, dual-headed bathymetry subsystem and single vertical beam sounder were repurposed as an extended nadir augmentation subsystem, which included triple-headed bathymetry and backscatter (C/P/S-ENAS) and a triad of single beam sounders that were physically configured to function as a vertical beam sounder (DL) and a port/starboard-looking Scatterometer. The DL and P/S Scatterometers are configured as a single replacement module that is readily accessible. It can easily be removed for calibration and re-installed. The Scatterometers function solely in the receive (Rx) mode. All other subsystems have both transmit (Tx) and Rx modalities.

I B: Cascading Sonar Calibrations

During the upgrade, the three-meter long port and starboard side scan sonar transducers (P-MBSS and S-MBSS) were mechanically back-focused (curved) to improve the spatial uniformity of the ensonification pattern. The fixed and time varying gains of the entire complement of 128 acoustic data channels were characterized under laboratory conditions. With the exception of the P/S-MBSS transducers, all acoustic transducers were removed from the system and calibrated to determine their frequency response, beam width in two axes and OCVR or TVR, as appropriate, based on their function in the upgraded 7180. In the future, when utilizing the schema described in this paper, it should only be necessary to re-calibrate the P/S Scatterometers.

Given that it is difficult/impractical to calibrate the source level of a three-meter long mechanically curved side scan array and the importance of the backscatter data being calibrated and radiometrically adjusted, a schema was developed for the 7180 that built on and extended the protocol for calibration of multibeam sonar [1]. In principal, the DL

The first author was working under NOAA Contract WE-133F-12-SE-1896.

source level can be predicted knowing the drive voltage that is applied to the transducer during Tx and knowing the DL's TVR that was determined in an acoustic calibration facility. Because the matching between the power amplifier and the Tx transducer may be less than ideal and introduce uncertainty concerning the as-built source level, it was considered good engineering practice to also perform a system through-put test with a standard target. The assembled, upgraded 7180 towfish was positioned in an acoustic tank where the DL Tx ensonified a standard target sphere. This type of tank test can reliably determine the sonar through-put, which is a "summation" of the source level and receiver sensitivity. Using the OCVR properties of the P/S-Scatterometers, that were determined in an acoustic calibration facility, the DL source level was separable from the system through-put. Echoes from the target sphere were analyzed in order to compute an as-built source level for the DL Tx pulse that will be used to provide a connection between the backscatter data and a known reference.

Although the C/P/S-ENAS, the DL and the MBSS subsystems employ different transmit waveforms and occupy different time allocations within the 7180's 1.1 sec inter-pulse interval, they provide backscatter information that is received on the Scatterometers from common cross-track sectors of the seabed. Therefore, the expectation that their resulting backscatter angular response functions should be highly correlated, affords a reliable means to estimate the as-built source level for the C-ENAS subsystem based on the DL source level and to estimate the as-built source levels for the P/S-ENAS based on the C-ENAS source level. In a like manner, data from the P/S-ENAS subsystems can cascade to the P/S-MBSS long-range side scan sonar subsystem through their overlapping sector of off-nadir angles in order to effectively tie their source levels together. Cascade calibration is intended to provide quality assurance of the backscatter values from the 7180 subsystems. This is accomplished through a scheme which ultimately relates the backscatter information from each subsystem to the known target strength of a standard target sphere. Cascade calibration is based on the fact that although the backscatter angular response function from a section of seabed may vary with acoustic frequency, time and azimuth, when it is observed using a system like the upgraded 7180, the backscatter angular response functions determined from the several subsystems are non-unique. The non-uniqueness (high correlation) is due to the narrow range of acoustic frequencies of the several acoustic subsystems, the significant spatial overlap of their measurement geometries and full radiometric treatment of their backscatter observations.

Neglecting noise, the temporal history of an "echo" from a single Tx pulse depends on: the altitude and attitude of the Tx and Rx transducers, the characteristics of the Tx pulse (length, coding and frequency content), the beam pattern of the Tx and Rx transducers, the bandwidth of the Rx channel, and the surficial sediment. The magnitude of the electrical signal representation of that "echo" depends on: the Tx source level, the gain (fixed and time varying) of the Rx channel, the OCVR of the Rx transducer, the altitude and attitude of the Tx and Rx transducers, and the transmission loss due to absorption. In principal, an adjustment can be applied to the backscatter signal for the effects of those factors on the "size and shape of an echo", except for the sea bed surficial sediments. The implication is that regardless of which subsystem emitted the Tx pulse, the backscatter angular response function derived through application of the appropriate adjustments to the Rx backscatter signals, will be numerically equivalent in the several overlapping off-nadir angular sectors of the subsystems. In the upgraded 7180, the pulse diversity and time division multiplexing of the several subsystems allow an entire set of inter-comparisons to be developed while operating in standard survey mode.

II. APPLICATION TO FIELD DATA

In the summer of 2012, the upgraded Klein Model 7180 was deployed from the NOAA Ship *Fairweather* and successfully operated on 645 nautical miles of survey tracks in the eastern Bering Sea [5].

Data acquired during that effort were subjected to the cascade calibration schema, which involves making a sequence of three connections between the observations of backscatter on the port and starboard Scatterometers that resulted from Tx pulses from the several subsystems.

The sequence provides relationships between the source levels of the DL, C-ENAS, P/S-ENAS and the P/S-MBSS Tx pulses. Those relationships provide the ability to assure that the processed backscatter from all of the 7180's acoustic subsystems can be traced to a common known reference, resulting in consistent backscatter data across the entire swath.

II A: Data extraction

The data from the port and starboard Scatterometers are specifically processed to isolate the Rx signals that resulted from the diverse transmissions from the several acoustic subsystems: the DL (Tx is a short CW pulse at the start of the system's second of three time divisions); the C-ENAS, which is the nadir pointing bathymetry and backscatter subsystem (Tx is a chirp pulse at the start of the system's first of three time divisions); the P/S-ENAS, which are bathymetry and backscatter subsystems that point to +/- 50 degrees from nadir (Tx is a chirp pulse at the start of the first of the system's first of three time divisions) ; and the MBSS, which is the long range side scan subsystem (Tx is a chirp pulse at the start of the third of the system's three time divisions). The three chirp pulses are orthogonal and were isolated from the composite Rx signals using standard pulse compression techniques. The backscatter resulting from the short CW (wide-band) pulse is separable from the sequence of Rx signals that occur during the 1.1 second inter-pulse interval, because its Tx is the only one that is active during the system's second of three time divisions. Leading edge detection of the first bottom return for each of the acoustic subsystems was employed in order to "stack" a large number of successive linear amplitude backscatter returns. The time of the first bottom return for the MBSS was determined indirectly from the leading edge detection of the DL Tx because the leading edge of the MBSS first bottom return was less distinct. Knowing the time of the MBSS Tx is delayed by 30 samples after the DL Tx and knowing the time of the DL Tx first bottom return, means that the time of the MBSS Tx first bottom return is also known.

Figure 1 presents the results of stacking 200 successive pulses that were acquired during normal survey operations where the 7180 was 82 m above the sea bed. In the case of the MBSS Tx, the peak at sample 20 is the bleed-thru of the wide-band pulse in the system's second time division into the pulse compression used to extract the backscatter due to the MBSS chirp Tx pulse in the third time division. In the case of the DL Tx, the second rise, which starts at time sample 90, is the bleed-thru of the uncompressed MBSS chirp Tx pulse in the system's third time division. These two instances of bleed-through do not create problems because they occur in sections of the stacked backscatter returns that are not used in the cascade calibration.

II B: First cascade connection

The first of three cascade connections that will ultimately tie together the source levels of all the 7180's acoustic subsystems is between the nadir pointing DL (whose source level has already been referenced to the target sphere) and the nadir pointing C-ENAS array. The engineering parameters that are common to the C-ENAS and the DL are the pointing direction of their MRA's and their Tx cross-track beam widths. The pointing directions of the C-ENAS and DL Tx transducers, in conjunction with their Tx beam response patterns, means that they are equally effective in providing ensonification of the port and starboard sides of the survey line. The Rx beam response pattern of the port and starboard Scatterometers, which are employed in all inter-comparisons of backscatter, in conjunction with the vertical pointing direction of their MRA's and the "yaw" orientation of their transducers, provides ample assurance that their Rx signals have arisen solely as a result of ensonification of either the port or starboard side of the survey track.

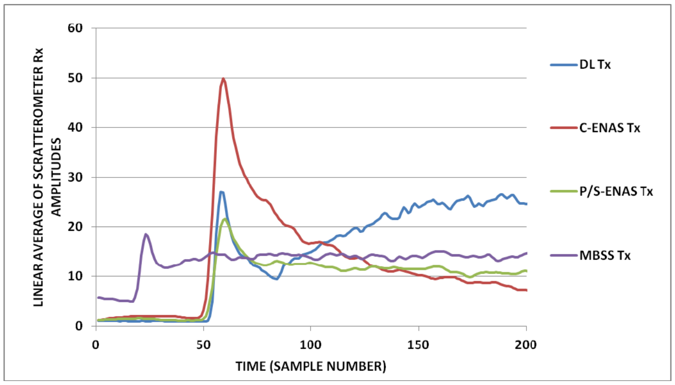

Figure 1 Stacks of signals that have been isolated from the Scatterometer Rx signals using their time and waveform diversity.

Figure 2 View of the 7180 tow fish's underside when it is suspended in the air.

The engineering parameters that differ between the C-ENAS and the DL are their Tx times within the 1.1 sec inter-pulse interval, their Tx pulse waveforms and the fore/aft position of their Tx on the tow body. Figure 2 shows the 7180 suspended in the air. The removable module that includes the DL Tx and the port and starboard Scatterometers Rx is marked with the blue arrow. The C-ENAS array (Tx and Rx) is marked by the yellow arrow.

Strictly speaking, the along track centers of the sea bed that are ensonified by the C-ENAS and the DL are not exactly co-located on any particular ping. There is a 2.5 m separation in the fore/aft positions of their Tx transducers on the tow body and, based on nominal survey speed of 3.5 m/sec, there is an additional 1 meter along-track center-to-center separation of the their MRA projections onto the sea bed, when the two Tx waveforms are emitted. However, at the nominal survey speed, the combination of the physical separation of their Tx transducers and the temporal separation of their Tx times, the sea bed that was under the DL on one pulse at the normal survey speed will essentially be under the C-ENAS on the next pulse.

During the signal analyses of their field survey data, adjustments are made to the backscatter signals arising from the C-ENAS and DL Tx pulses that take into account the differences in design and implementation of those two subsystems. An important issue for connecting the C-ENAS source level to the DL source level, through the P/S Scratterometer Rx, is the difference between the DL and C-ENAS Tx waveforms. The latter, a chirp, is twenty times as

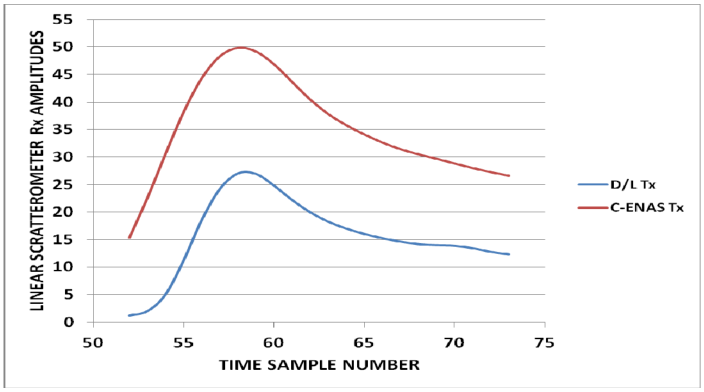

Figure 3 Synchronous stacks of "first" bottom returns from the C-ENAS and the DL prior to application of adjustments associated with pulse length.

long as the former, which is a short CW pulse. Pulse compression is applied to extract the first bottom return of C-ENAS related backscatter from the Scatterometer Rx. No pulse compression is required to extract the first bottom return of the DL related backscatter from the Scatterometer receiver. Figure 3 presents the synchronously stacked "first" bottom returns from the C-ENAS and the DL. The pre-compressed C-ENAS backscatter and DL backscatter are influenced by both the sea bed backscatter angular response function and the vertical beam pattern of the Scatterometer Rx transducer. However, due to the difference in their Tx pulse lengths, the instantanous formulation of their backscatter signals are goverened by different angular sectors of the sea bed backscatter angular response function and different angular sectors of the Scatterometer Rx beam response. The "long pulse" influence due to the sea bed can be estimated using the time history of the backscatter that is received on the Scatterometers as a result of the DL Tx (short CW pulse). The "long pulse" influence of the Scatterometer Rx vertical beam response can be estimated by performing an average over the affected section of the Scatterometer response, expressed in linear amplitude, rather than decibels.

When adjusted for the impacts of pulse length, the observed differences between the linear average "peaks" of the C-ENAS Tx and DL Tx received on the P/S-Scatterometer during normal survey operation provide information that can be used to estimate the C-ENAS source level, relative to the DL. Based on that information, it is concluded that the C-ENAS source level is 2.5 dB higher than the DL source level.

II C: Second cascade connection

The second of three cascade connections that will ultimately tie together the source levels of all the 7180's acoustic subsystems is between the nadir pointing C-ENAS bathymetry and backscatter array and the P/S-ENAS bathymetry and backscatter arrays that point to +/- 50 degrees from nadir. The Tx times for the C-ENAS and the P/S-ENAS are identical, as are their Tx beam patterns relative to MRA. Pulse compression is used to isolate and extract the C-ENAS and P/S-ENAS backscatter from the Scatterometer Rx signals. The 100 degree difference between the off-nadir mechanical pointing angles of the P-ENAS Tx and the S-ENAS Tx and the 80 degree difference between the off-nadir mechanical pointing angles of the P/S Scatterometer make it possible to identify the backscatter associated with a particular Tx pulse. The chirp waveforms for the C-ENAS and P/S-ENAS are orthogonal. Their pulse lengths are identical.

The comparison of source levels for the C-ENAS and the P/S-ENAS is based on linear amplitude ratios of their backscatter signals received on the same transducer (port or starboard Scatterometer), in comparison to the expected ratio of linear amplitudes based on the system hardware. The system ratio was developed using the off-nadir beam responses of the C-ENAS and the P/S-ENAS, which differ due to the 50 degree offset between their MRA pointing angles. If, for example, the source level of the C-ENAS and the P-ENAS were equal, then the expected ratios over an off-nadir angular sector, based on the system hardware, would be identical to the observed ratios of linear amplitudes the C-ENAS and P-ENAS backscatter in that same off-nadir sector. Figure 4 presents the ratios of stacked backscatter that were received on the Scatterometer along with reference lines for half-system, unity-system and twice-system response ratios. The half-system ratio represents a P/S-ENAS source level that is 6 dB relative to the C-ENAS source level and the twice-system ratio represents a P/S-ENAS source level that is -6 dB relative to the C-ENAS source level. The curve denoted as DATAC/PS-31 is the ratio of C-ENAS to P/S-ENAS backscatter amplitudes that were received on channel-31, which means the Tx being compared to the C-ENAS Tx was the P-ENAS. The curve denoted as DATAC/PS-32 relates to the S-ENAS Tx. Because their amplitude ratios with the C-ENAS lie close to the unity system ratio, both the P-ENAS Tx source level and S-ENAS Tx source level are close to the C-ENAS source level. Further detailed analyses indicate that the P-ENAS Tx source level is -0.3 dB, relative to the C-ENAS Tx source level and the S-ENAS Tx source level is 0.4 dB, relative to the C-ENAS Tx source level.

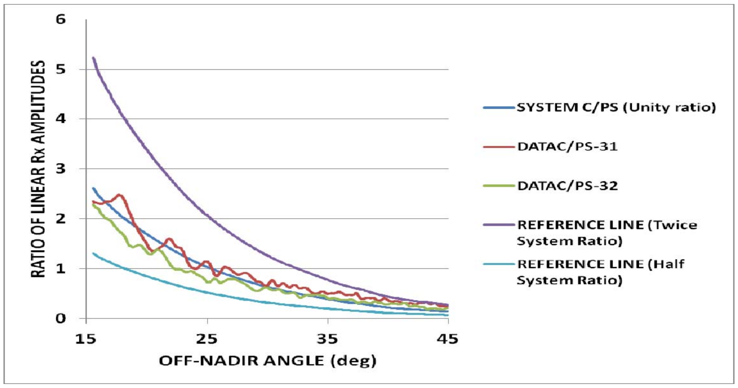

Figure 4 Comparison of predicted system response ratio between C-ENAS and P/S-ENAS with ratios between C-ENAS and P/S-ENAS that were observed during normal survey operations.

II D: Third cascade connection

The third of three cascade connections that will ultimately tie together the source levels of all the 7180's acoustic subsystems is between P/S-ENAS bathymetry and backscatter arrays that point to +/- 50 degrees from nadir and the MBSS side scan arrays that point to +/-70 degrees from nadir. The transmit times for the P/S-ENAS and P/S-MBSS are not identical, nor are their vertical response beam patterns identical. Pulse compression was used to isolate and extract the P/S-ENAS and MBSS backscatter from the Scatterometer Rx signals.

The backscatter from the P/S-ENAS and MBSS were synchronously "stacked" for a large number of successive pings, based on the times of their respective first bottom returns. Figure 5 presents the ratios of P/S-ENAS backscatter to P/S-MBSS backscatter in a fashion similar to Figure 4. The P/S-MBSS effective source level asymptotically increases from a base level as the slant range increases. This effect stems from the fact that at short ranges the full length of the Tx array does not contribute to the ensonification of the sea bed. In addition to differences between the off-nadir Tx beam responses of the P/S-ENAS and the P/S-MBSS, the expected system ratio in Figure 5 includes a term that is altitude dependent because of the inter-relationship between off-nadir angle and the slant range that is required for computing the MBSS's effective source level. The Data Ratio 31 and 32 curves run above the system reference line indicating that P/S source levels are higher than the P/S-MBSS base source levels. Further detailed analyses indicate that the port MBSS Tx base source level is -3.2 relative to the P-ENAS Tx source level and the starboard MBSS Tx base source level is -3.3 dB, relative to the S-ENAS Tx source level.

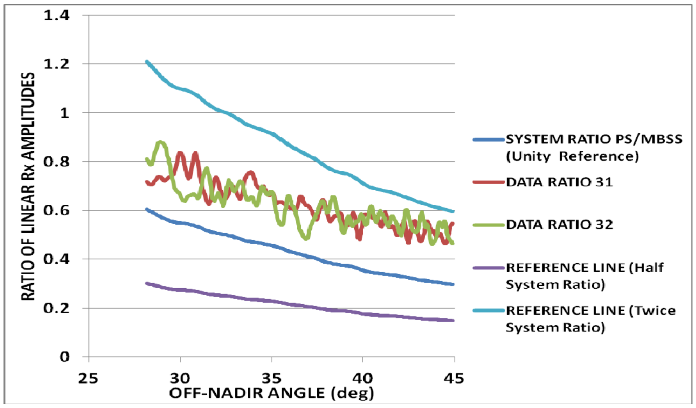

Figure 5 Comparison of predicted system response ratio between P/S-ENAS and P/S-MBSS with ratios between P/S-ENAS and P/S-MBSS that were observed during normal survey operations.

III. CONCLUSIONS

A schema has been described and demonstrated in terms of connecting estimates of the as-built source levels for the several backscatter subsystems of the upgraded 7180 Long-Range, Fishery-Research Side Scan Sonar to a known reference. The schema is also applicable to making connections between the 7180's several acoustic subsystems in terms of through-put and receiver sensitivity. Whether the schema is applied to the through-put, source levels, or the receive sensitivities, the cascade sequence starts with a target sphere and goes to the DL, then to the C-ENAS, and then separately to the P-ENAS and to the S-ENAS. The cascade sequence continues with the P-ENAS connecting to the P-MBSS and the S-ENAS connecting to the S-MBSS. The cascade sequence provides the ability to reference the 7180's backscatter levels to a recognized standard. The technique also provides a measure of quality assurance by virtue of the ability to continually make inter-comparisons between spatially overlapping measures of backscatter during normal survey operations. This schema advances the fishery research goal of consistent seabed characterization across wide swaths of the seabed.

ACKNOWLEDGMENTS

We gratefully acknowledge expert at-sea support by S. Intelmann (AFSC), Naval Undersea Warfare Center (Keyport) personnel M. Moody, E. Draper, B. Heather, J. Hosford, and J. Husted, and also the officers and crew of NOAA Ship *Fairweather*. Funding was provided by the RACE Division at the AFSC.

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