A method for a relative sonar field calibration using Reson 7125 multibeam echo-sounders

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Abstract

Acoustic seafloor backscatter measurements made by multiple Reson multibeam echo-sounders (MBES) used for hydrographic survey have been observed to be inconsistent, affecting the quality of data products and impeding large-scale processing efforts. A method to conduct a relative *inter* and *intra* sonar calibration in the field using dual frequency Reson 7125 MBES has been developed, tested, and evaluated to improve the consistency of backscatter measurements made from multiple MBES systems. The approach is unique in that it determines a set of corrections for power, gain, pulse length, and an angle dependent calibration term relative to a single Reson 7125 MBES calibrated in an acoustic test tank. These corrections can then be applied during processing for any acquisition setting combination. This approach seeks to reduce the need for manual data or data product manipulation during post processing, providing a foundation for improved automated seafloor characterization using data from more than one MBES system.

Introduction

Background and Problem Statement

The information provided by acoustic seafloor backscatter can be used for a wide variety of science, engineering, and management applications ranging from underwater construction , fisheries habitat, and object detection and identification. Because of the diverse array of applications, seafloor backscatter measurements are increasingly being recorded in conjunction with bathymetric measurements to capitalize on vessel time during hydrographic surveys. However, although acoustic scattering is a stochastic physical process, the difference in the central tendency of measurements made by different multibeam echo-sounders (MBES) of the same manufactured model over the same seafloor are observed to be inconsistent. Since the use of multiple MBES on a single hydrographic survey is a common operational paradigm within large hydrographic survey organizations, backscatter measurement inconsistencies significantly detract from the visual quality of backscatter products such as mosaics, and impede the use of manual and automated seafloor segmentation and/or characterization routines. The goal of this work is to reduce this kind of backscatter measurement inconsistency.

The problem is regularly apparent in backscatter mosaics at the geographic junction of adjacent data acquired with multiple systems, a situation further complicated by the use of different acquisition settings with each system. Figure 1 is an example of a typical backscatter mosaic made from data from four different Reson 7125 MBES in which the backscatter measurement inconsistencies between systems and settings are visually apparent.

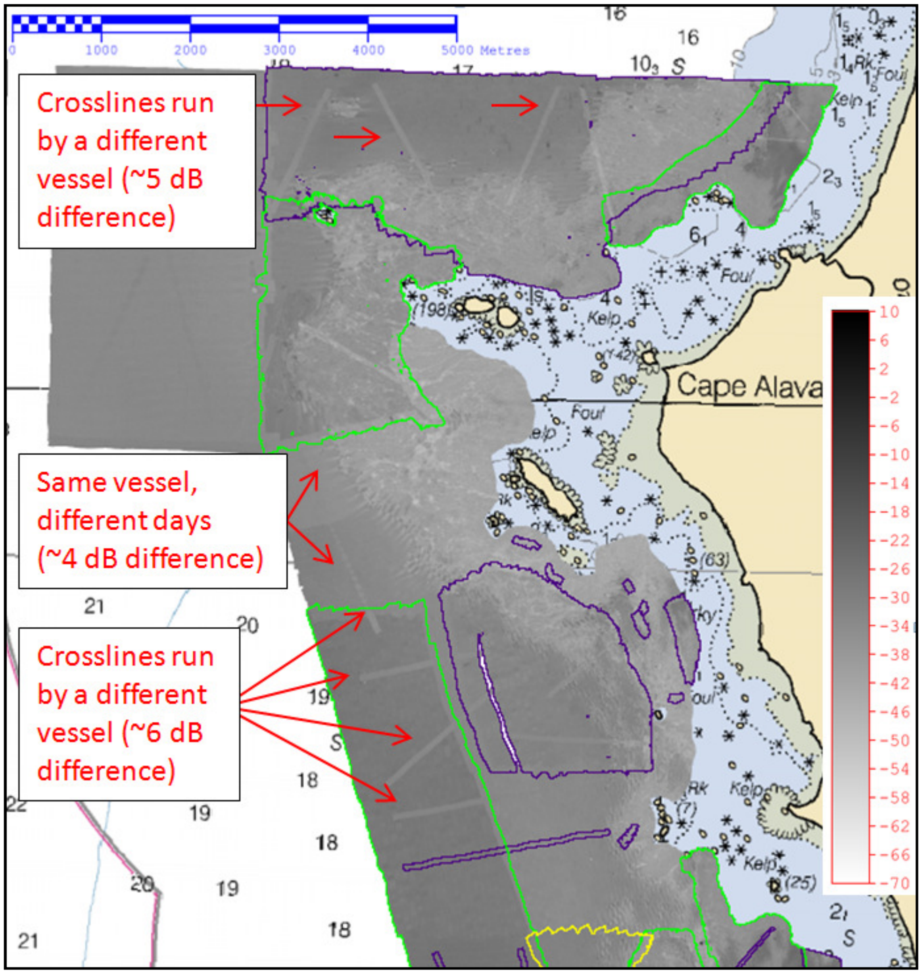


Figure 1: Backscatter mosaics from a NOAA hydrographic survey H12221 off the coast of Washington state. Data acquired in 2010 processed with Fledermaus Geocoding Toolbox (FMGT) in 2013 using data from four different 400-kHz Reson 7125 MBES systems mounted on different vessels: Launch 2805 (no outline), Launch 2806 (purple), Launch 2807 (green), Launch 2808 (yellow).

Assuming the backscatter reduction process incorporates well measured and/or well modeled water column and seafloor geometry, and that any biases introduced by the processing reduction routine employed such as the insonified area estimate or sample selection are the same for all MBES systems, then the lack of radiometric calibrations is a reasonable explanation for measurement inconsistency. The solution to this is, of course, to acoustically calibrate the systems, however, absolute acoustic calibration in a test tank for every MBES is cost-and-time-prohibitive. A standard target calibration, in the field, with shallow water MBES mounted on small vessels poses physical challenges to positioning the target in the far field of all the beams. The field calibration proposed by Lanzoni (Lanzoni and Weber, 2011) requires a calibrated split-beam echo-sounder to position the target, the mounting for which also poses a challenge for use on small vessels, and has not yet been tested in the field. The additional effort required to set up these kinds of calibrations also scales with each additional system to be calibrated, and is excessive if all that is desired is consistency in measurements between systems.

A relative calibration is a reasonable alternative. Greenaway and Rice derived a single-value offset between two Reson 7125 SV2 MBES operating simultaneously on the same ship by differencing the averaged backscatter data acquired over a large geographic area that was processed in commercially available software (Greenaway, 2013). However, the systems were operating on the same hull at the same time and the derived offsets between the two systems were found to vary with time and/or location, likely due to different settings and system normalizations (a specific feature of Reson 7125 MBES to normalize amplitude and phase differences between the receiver elements).

Proposed Solution

This work proposes a compromise between existing absolute and relative calibration approaches to achieve consistent absolute backscatter estimates from multiple MBES systems via a field method devised to relatively calibrate multiple MBES systems against a system calibrated in an acoustic test tank at the University of New Hampshire. The approach is unique in that it:

1) Applies acoustic tank measurements of the angular-dependent calibration coefficient, source level, gain, and beam widths performed at a fixed range and a single power, gain, and pulse length setting to reflectivity field data collected by the tank calibrated MBES to estimate the absolute scattering strength of a particular patch of seafloor to create a calibrated target area;

2) Uses the absolute scattering strength estimate of the calibrated seafloor target from the tank calibrated system to transfer the absolute calibration to an uncalibrated system by using the uncalibrated system to measure the same patch of "calibrated seafloor" for one single set of settings (*inter* calibration); and

3) Measures the response of the field calibrated system at all other possible settings other than those used to measure the "calibrated seafloor" and develops corrections for them (*intra* calibration).

The proposed result is a set of four correction look-up tables (LUT): one to account for the angle-dependent calibration coefficient at a single, fixed set of settings relative to the tank-calibrated system; and the other three to account for how the field calibrated system responds to changes in power, gain and pulse length settings relative to those used to measure the calibrated seafloor. Though the ability to apply such corrections does not currently exist in commercial processing software, the set of four correction tables are envisioned to be incorporated into the backscatter reduction process for any operational setting combination and are expected to eliminate the need for setting specific data processing (e.g. unique single-value combined corrections for each setting combination), or data product manipulation such as the use of non-linear color maps.

Methodology

Each individual backscatter estimate from each beam is the result of accounting for a collection of stochastic processes associated with the equipment, the medium, and the target (Urick, 1967). That is, each measurement is affected by the MBES's ability to transmit and receive sound, the vehicle on which the MBES is mounted, and the collective response to the environmental conditions in which the system is operated; the media through with the sound is propagated; and the properties of the seafloor. The goal is to correct for the equipment and media such that the measurement only represents the seafloor.

Recognizing that each vessel introduces its own acoustic noise characteristics to the problem from vibrating machinery such as engines, generators, and propellers (Burdic, 1984), each relative calibration between "systems" pertains to the collective difference between each MBES-vessel pairing. If MBES-vessel components were to be separated, reconfigured, or replaced, the relative calibration is expected to change, but could be reacquired with the new configurations.

The field calibration procedure is conceived to take place in two stages: one in which the reference MBES (tank calibrated 7125 in this case) acquires data over the same patch of seafloor as the MBES to be calibrated, as near in time as possible to determine the angle-dependent calibration term C; and the second in which each vessel is stationary while the uncalibrated MBES pings through a range of system setting combinations over the same seafloor with as little acoustic interference as possible to determine setting corrections for power, gain, and pulse length relative to the settings used to acquire C (referred to here as "pivot settings"). The pivot settings are the unique power, gain, and pulse length settings used to acquire the *inter* calibration data. The *intra* calibration is designed to measure how the system responds to settings relative to the pivot settings and to develop corrections for them. The corrections for the pivot settings within the LUTs that are the result of the *intra* calibration are necessarily zero by design.

The *inter* calibration transfers a reference standard level to the uncalibrated system for a single setting combination of power, gain and pulse length. If the newly calibrated system were only to be operated at these settings, the system would produce measurements that are calibrated. Operating only using a single set of setting combinations or performing an *inter* calibration for all setting combinations is an impractical imposition upon field operations; thus the calibration standard must be transferred to all other possible settings of power, gain and pulse length in the newly calibrated system. The *intra* calibration is a procedure that seeks to transfer the *inter* calibration to other power, gain, and pulse length settings by measuring how the sonar responds when operated at all other setting combinations. The *intra* calibration results in correction tables relative to the *inter* calibration pivot settings (pivot settings have a zero correction) that account for how the system responds when settings other than the pivot settings are used. The *inter* sonar calibration is a function of the beam steering angle and the resulting calibration is applicable regardless of the beam forming mode (e.g. equiangular or equidistant with or without roll stabilization enabled). The *inter* and *intra* calibrations for the same pivot settings are taken as a set.

Backscatter Processing

Starting from a modified conventional sonar equation in which the units are all in dB (Urick, 1967):

$$\mathrm{EL} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS} \qquad [1]$$

where EL is the echo level:

$$\mathrm{EL} = \mathrm{DN} - \mathrm{G} - \mathrm{C} \qquad [2]$$

where DN is a digital number representing the complex amplitude envelope of the pulse on the seafloor recorded by the sonar taken from the Reson 7006 amplitude record associated with the seafloor detection of each beam; C is a calibration coefficient term that accounts for the way the sonar mechanically responds to pressure waves and converts them to electrical signals (i.e. the way the sonar transduces, digitizes, steers beams, etc) taken from the tank calibration, field calibration, or a fixed, commonly used default value of -100 dB; and G is the applied gain setting from the Reson 7000 record adjusted by the time-varying Reson applied gain derived from a proprietary formula for each beam plus a setting correction from tank calibration measurements, G_{tank}, or field calibration measurements, G_{field};

SL is the source level emitted from the sonar and is taken to be the operator-selectable Reson power setting from the Reson 7000 record plus a setting correction either derived from tank calibration measurements, SL_{tank}, or field calibration measurements, SL_{field} if available, both in dB re Reson;;

TL is the transmission loss through the water column:

$$\mathrm{TL} = 20\log_{10}\mathrm{r} + \alpha r/1000 \qquad [3]$$

where r is the ray traced slant range to the seafloor for each beam in m and α is the harmonic mean of the absorption coefficient profile calculated for each sound speed profile depth bin in dB/km;

and TS is the target strength:

$$\mathrm{TS} = \mathrm{S_b} + 10\log_{10}(\mathrm{Area}) \qquad [4]$$

where S_b is the unit area scattering strength and Area is the insonified area of the beam taken to be the minimum of either:

$$\frac{\psi_{tx}\, c\tau r}{2\sin(\theta_{ix})\cos(\theta_{iy})}, \qquad [5]$$

the pulse length limited area (typically applicable for the outer beams), or

$$\frac{\psi_{tx}\psi_{rx} r^2}{\cos(\theta_{ix})\cos(\theta_{iy})}, \qquad [6]$$

the beam width limited area (typically applicable for near-nadir beams where $\psi_{tx}$and ψ_{rx} are the -3 dB (half power) transmit and receive beam widths in radians taken to be either those specified by the manufacturer or those measured in the tank, *c* is the sound speed at the depth of the seabed measured by the CTD profile in m/s, τ is the pulse length setting in s, θ_i is the true angle of incidence with the seafloor accounting for the beam ray path and the local across-track slope of the seafloor in radians, and θ_s is the steering angle corrected for vessel mounting biases relative to the inertial measurement unit (IMU) and possibly real time vessel roll, depending on the data record version used and whether roll stabilization is enabled (Lurton et al., 1994).

Solving the expanded for of equation [1]:

$$\mathrm{DN} - \mathrm{G} - \mathrm{C} = \mathrm{SL} - 2\mathrm{TL} + [\mathrm{S_b} + 10\log_{10}(\mathrm{Area})] \qquad [7]$$

for $\mathrm{S_b}$, we arrive at what is here referred to as the backscatter measurement:

$$\mathrm{S_b} = \mathrm{DN} - \mathrm{C} - \mathrm{SL} + 2\mathrm{TL} - 10\log_{10}(\mathrm{Area}) - \mathrm{G} \qquad [8]$$

For each ping: the user-selected single setting value for power, gain, absorption, spreading, and pulse length, as well as the frequency, *f*, the surface sound speed, c_s, and roll compensation status and datagram version are obtained from the Reson 7000 record; the vessel navigation is taken from the Reson 1003 record; vessel heave, pitch, and roll are taken from the Reson 1012 record; and vessel heading is taken from the Reson 1013 record. For each beam in each ping: the digital sample associated with the Reson seafloor detection (dn) is taken from the Reson 7008 record; the two-way travel time (*twtt*) is taken from the Reson 7006 record; and the steering angle (θ_s) is taken from the Reson 7004 record for earlier datagram versions or the 7027 for later datagram versions enabled (Reson 7004 record steering angles are in the vertical reference frame if roll stabilization is enabled and are in the MBES reference frame if roll stabilization is disabled; steering angles from the Reson 7027 record and are in the MBES reference frame regardless of whether roll stabilization is enabled or not). Beam data for which quality seafloor detections (passes Reson filters for brightness, colinearity, and depth) are not achieved and pings for which navigation information does not exist are removed from the dataset prior to processing into $\mathrm{S_b}$. Tank or field corrections for each term in equation [8] can be applied.

Reson 7125 Tank Calibration

A dual frequency Reson 7125 SV1 with independent projectors for each frequency (200 kHz and 400 kHz) was calibrated in the test tank at the University of New Hampshire in the spring of 2012 using the standard sphere approach with a TC 4034 calibrated hydrophone. A technical report describes each tank calibration measurement and its results (Lanzoni, 2012). The tank calibration measurements that were used for this work are the system responses to power and gain settings, the calibration term a s function of beam steering angle, and the combined 3-dB beam widths, all performed at a range of 8 m with the same relative settings. Calibration measurements not used included independent transmitted and received pulses at fixed ranges and settings, and an evaluation of saturation. Uncertainty estimates were not reported.

Inter Field Calibration Procedure

Two MBES on two separate vessels are used to measure the same area of seafloor as near in time as possible and the difference between the two is used to determine $C(\theta_s)$ for the uncalibrated system using a single set of settings. The seafloor is the calibration target. This exposes the result of the test to uncertainty from nearly all of the terms in the backscatter reduction calculation presented in equation [8]. It is therefore necessary to carefully consider the conditions of the seafloor, water column, and surface dynamics, as well as how well each can be measured and/or modeled when selecting the location and time to acquire the data using a standard planned survey line. In general, it is desirable to select a time and location at which the seafloor, water column, and sea surface properties are most stable; and where this cannot be achieved, a line length, ping rate, and depth to obtain a sufficient number of pings such that the biases in potential sources of interference are the same for each system, or are negligible.

Once the site is selected and the line azimuth and length is determined, the coincident line is run in the same direction by both vessels with all the MBES and all other ancillary echo-sounders not transmitting. A salinity and temperature water column profile measurement (CTD) is taken immediately before and after MBES acquisition at a minimum to verify the assumption of oceanographic stability of the water column. If the MBES are at risk of being operated in a saturated setting regime, care should be taken to select operational settings that ensure all systems are operating in a linear regime while maximizing the number of quality bottom detections across the swath for most if not all beams. The data from each line acquired by each system is processed into S_b and the beam means are differenced to derive C_{field}.

As this work is geared toward working with multiple Reson 7125 systems operated by NOAA, the Reson .s7k sonar file (Reson, 2011); a Seabird conductivity, temperature, and depth (CTD) .cnv profile file (Sea-Bird Electronics, 2013); and a CARIS .svp sound speed profile file (CARIS, 2012) are all used to reduce the raw digital number associated with the seafloor detections recorded in the Reson .s7k files into estimates of seafloor scattering strength, S_b. While much of the approach is specific to operational controls and parameters of the Reson

7125, and to file types and data acquisition and processing workflows currently used by NOAA hydrographic field units, this approach is theoretically adaptable to other data formats and acquisition paradigms.

Intra Field Calibration Procedure

The *intra* calibration uses the change in recorded amplitude of each seafloor detection for each setting change of either gain, power, and pulse length, holding the other two settings constant. The purpose is to determine setting corrections for all possible setting combinations other than the pivot settings used during the *inter* calibration test. This method uses sample statistics to determine the central tendency of each MBES' response to changes in settings. Each amplitude measurement from each beam is assumed to be an independent sample described by a Normal distribution when the MBES is pinging at a stationary, ergodic, homogenous seafloor from a fixed position.

Many of the seafloor, water column, and sea surface characteristics desirable for the *inter* calibration site are also desirable for the *intra* calibration site. The physical set up is somewhat less constrained in that the requirement to have two vessels over the same patch of seafloor near in time does not exist, yet it is more sensitive to small perturbations on the seafloor, in the water column, or on the sea surface because a small number of pings are compared to successive set of pings at another set of settings.

An ideal depth and seafloor type that accommodates all setting combinations for the Reson 7125 has not been identified. That is, a depth for which the seafloor is detectable in the beam-formed amplitude using lower setting values, but does not saturate received signals made using higher settings has not been identified. From a practical perspective, shallower depths on the order of 5-10 m are preferable so that a faster ping rate can be used to decrease the overall length of time it takes to complete the test, and also to minimize exposure of each ping to discrete interference events in the water column (e.g. kelp leaf in the water column passing under the boat). Even if an ideal depth and seafloor type exists, finding it over a span of homogenous seafloor alongside a pier, in a mooring field or anchorage area, or in a low trafficked area is unlikely. Ultimately the merits and limitations of each potential site available within a given area must be considered individually and weighed against each other to choose the best available site.

A large number of pings at each setting combination theoretically increases the confidence in the result, but also increases the risk of induced biases from the dynamics of the water column or seafloor. If the assumptions of a homogenous, stationary seafloor and water column can be preserved for seconds at a time, a target confidence interval or precision of the sample mean can be used to determine the sample size. The number of pings at each setting combination used in the field case studies varied between 15-30 pings.

The particular model of Reson 7125 MBES (SV1) used allows users to select gain settings ranging from 0 to 83 dB in intervals of 1; power settings ranging from 170 to 220 dB in intervals of 1; and pulse length settings from 33 to 300 μs in intervals of 1 μs up to 100 μs, and in intervals of 10 μs up to 300 μs. Logging all possible combinations would take days and; therefore the *intra* calibration was performed during the case study using several different down-sampled setting selections with different setting step intervals. This is considered acceptable because the Reson 7125 amplitude response to gain and power setting changes is assumed to be linear as there are no previous observations to suggest otherwise.

A script to command setting changes after every 30 pings at each setting combination originally written by Rice for a saturation monitoring tool (Rice, 2012) was modified and used to log the *intra* calibration data. To log a sample of pings at each setting combination, first the pulse length is set, then the power, and finally the system is then cycled through the range of gain settings. After logging through all gain settings with the pulse length and power fixed, then the power setting is changed, and the gain cycle is repeated. This process continues through all the remaining settings for power and pulse length. The spreading and absorption is set to zero throughout the test to avoid the need to correct for Reson applied TVG. The fixed Reson depth gates are also set tightly around the seafloor to avoid erroneous seafloor detections.

Because the *intra* calibration is expected to be performed in relatively shallow water depths, the systems are expected to saturate at higher setting values for power and gain. To find the linear region of the SL_{field} and G_{field} at which it is assumed saturation did not occur, the SL_{field} and G_{field} values are linearly regressed onto their corresponding settings, first using all settings and then by successively removing the next highest setting. The R-squared value and 95% confidence interval (CI) for each regression are computed. The highest setting that results in the largest R-squared value (below 1, i.e. more than two settings) and minimum CI is taken to be the maximum setting within the linear operational regime of the MBES during the test. The minimum setting value is taken to be smallest operational value of the setting. The linear, non-saturated setting corrected values are extrapolated to derive corrections for the saturated settings, resulting in the final *intra* calibration LUTs for the power and gain settings. Alternately, the test could be performed in several depth ranges (e.g. shallow, medium, deep), and the linear setting regions of each could be combined. A full comparison between the two approaches has not been achieved. A linear approximation of the field data is considered suitable as that is what has been observed in the test tank.

The pseudo PL correction is determined by calculating the difference between the expected changes (EΔ) in dB for the pulse length used relative to the pivot pulse length where the expected change in dB is:

$$\mathrm{E}\Delta = 10\log_{10}(\tau_i) - 10\log_{10}(\tau) \qquad [9]$$

which is what would be used in the insonified area term of the backscatter calculation in equation [8], all other terms being equal. The pseudo pulse length correction is the difference between what is expected and what was measured in the field:

$$\text{pseudoPL} = \text{E}\Delta - \Delta DN_{p,g,\tau_i} \qquad [10]$$

where $\Delta DN_{p,g,\tau i}$ is the change in dB when using other pulse lengths other than the pivot pulse length at the pivot power and gain settings. The pseudo PL correction is intended for all beams, regardless of how the insonified area is defined, as the correction accounts for an observed system amplitude response to all beams and is not a correction for the length of time the pulse is emitted or for the shape of the pulse.

Figure 2 shows an example result of both the *inter* and *intra* field calibration set of corrections for the following pivot settings: power 200, gain 20, and pulse length of 120. The plotted solid green line in each plot is the look-up table of corrections used to calculate $\mathrm{S_b}$. The data plotted in red is the raw field data from which the corrections in green are derived.

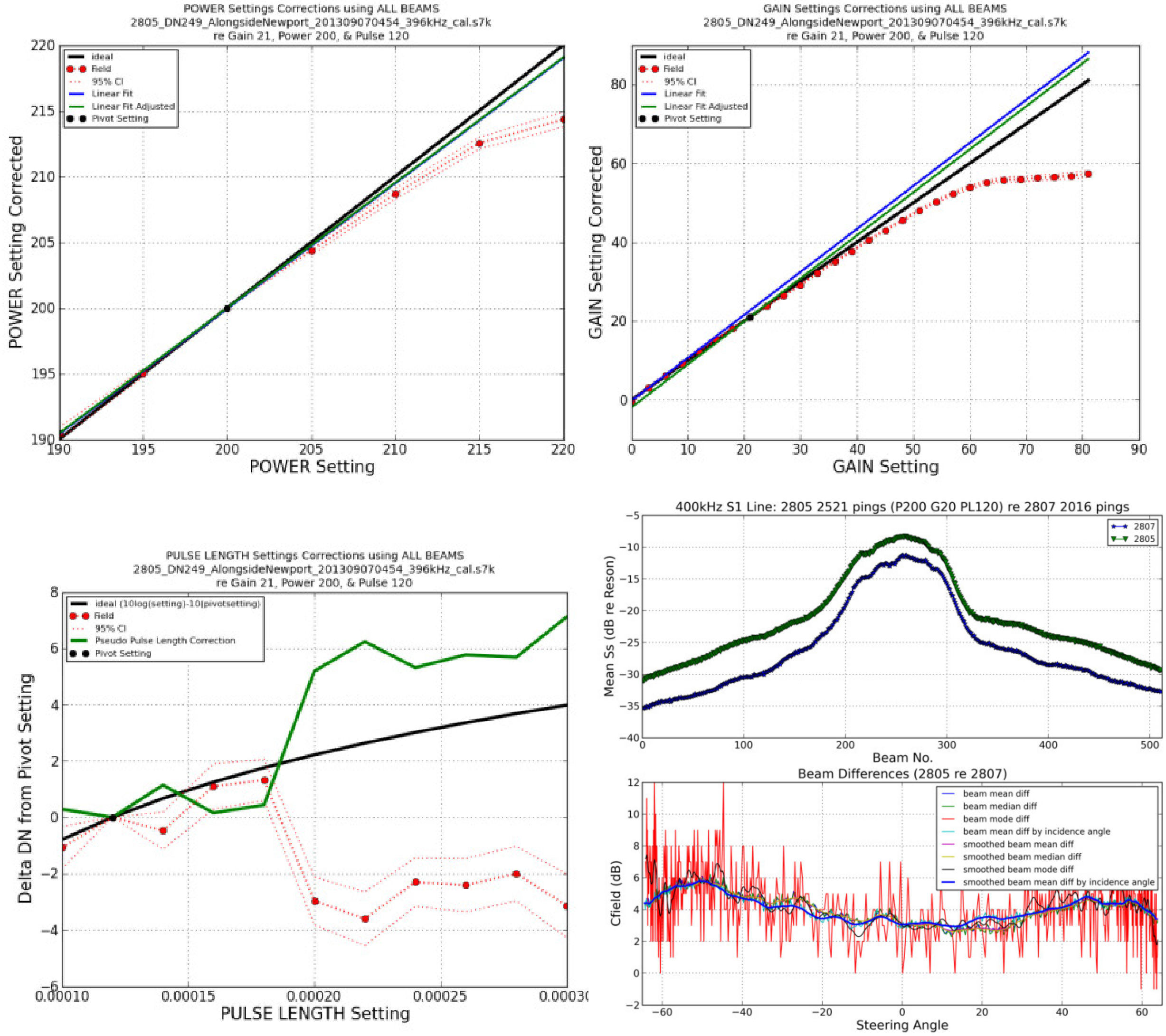


Figure 2: Example result of the inter and intra field calibration SL_{field} (upper left), G_{field} (upper right) $pseudoPL_{field}$ (lower left), and C_{field} (lower right).

Field Calibration Results (Newport, OR)

NOAA Ship *Fairweather* carries four 10-m survey launches of the same design. Each launch is referred to by its unique hull number: 2805, 2806, 2807 and 2808. Figure 3 shows the launches alongside the NOAA small boat pier in Newport, Oregon, in September, 2013.

Figure 3: NOAA Survey Launches 2805, 2806, 2807, and 2808 in Newport, Oregon.

Each launch is equipped with a dual-frequency Reson 7125 SV1 MBES with separate 200-kHz and 400-kHz projectors, a Reson real-time surface sound speed sensor, an Applanix POSMV position and attitude sensor, and a Seabird CTD for conductivity, temperature, and pressure profiling with which to model the sound speed profile through the water column.

Inter Calibration ($C_{field'}$)

The *inter* calibration procedure was executed at three different sites – in 10 m water depth in the Yaquina River (Site 1), in 20 m water depth 2 NM off the coast of Newport (Site 2); and in 40 m water depth 4 NM off the coast of Newport (Site 3) – with three systems using different pivot settings to verify the repeatability of the approach across a range of system settings and locations (Figure 4). The settings at each location were selected in situ with a Saturation Monitor tool that estimates when the system is saturating (Rice, 2012). The *inter* calibration survey lines were run in both directions with each set of settings. The systems on Launch 2805 and Launch 2806 were calibrated against the tank-calibrated system on Launch 2807.

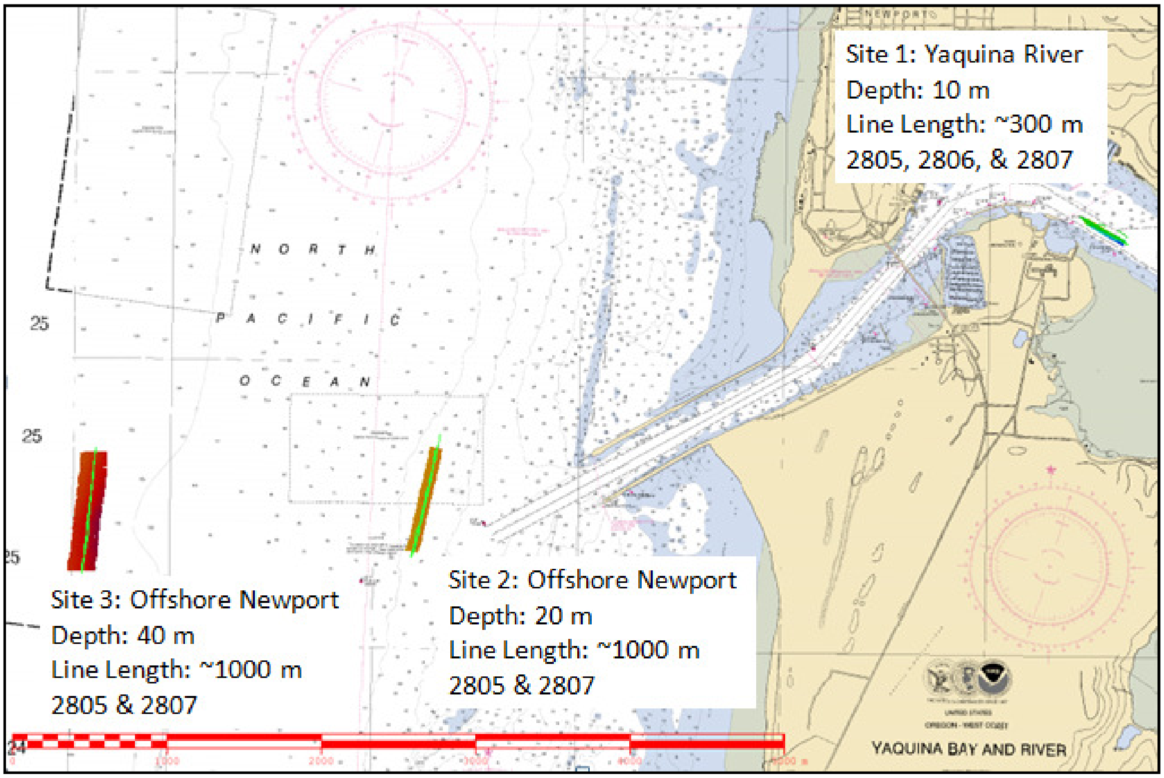


Figure 4: Inter calibration sites in and around Newport, Oregon (NOAA Chart 18746).

The Launch 2805 system was calibrated at all three sites using five setting combinations over the course of two days. The Launch 2806 system was calibrated at Site 1 only, using the same set of settings four times. All systems were calibrated at both frequencies in equidistant mode with roll stabilization enabled. During all tests, data were logged both in Hypack on a separate acquisition computer and by the Reson controller software on the Reson 7P processor. The data were logged in Hypack because that is the traditional acquisition method of the ship, but also with Reson 7kCenter to record water column data as well.

The *inter* calibration data were first processed as a simple relative calibration without tank calibration corrections. This was done both to assess the initial differences between systems. Depending on the setting combinations used, the relative differences are consistent with previous observations, varying between tenths of a dB to 5 dB.

Figure 5 shows the results of the 200-kHz relative *inter* calibrations $C_{field}(\theta_s)$ for the Launch 2805 system at all three sites using different pivot setting (A, B, and C), and for the Launch 2806 system at Site 3 using only one setting repeated several times (D). Figure 6 shows the same for the 400-kHz systems, though the pivot settings are different.

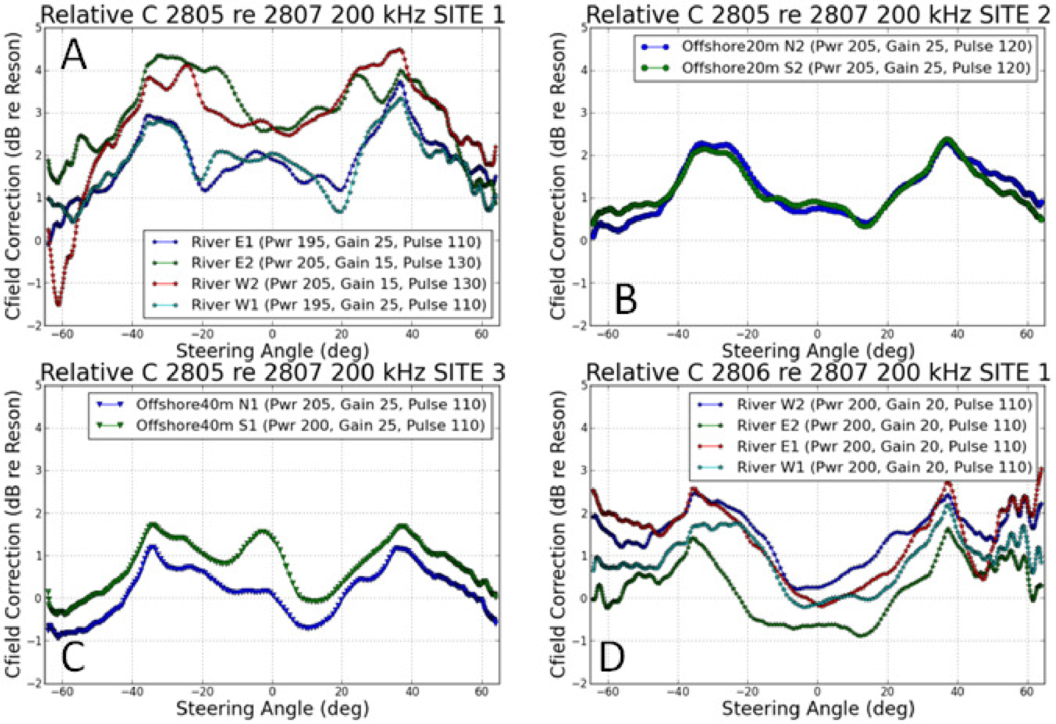


Figure 5: Relative 200-kHz $C_{field}(\theta_s)$, for Launch 2805 system at Site 1 (A), Site 2 (B), Site 3 (C) and for Launch 2806 system at Site 3 (D) relative to the pivot settings used.

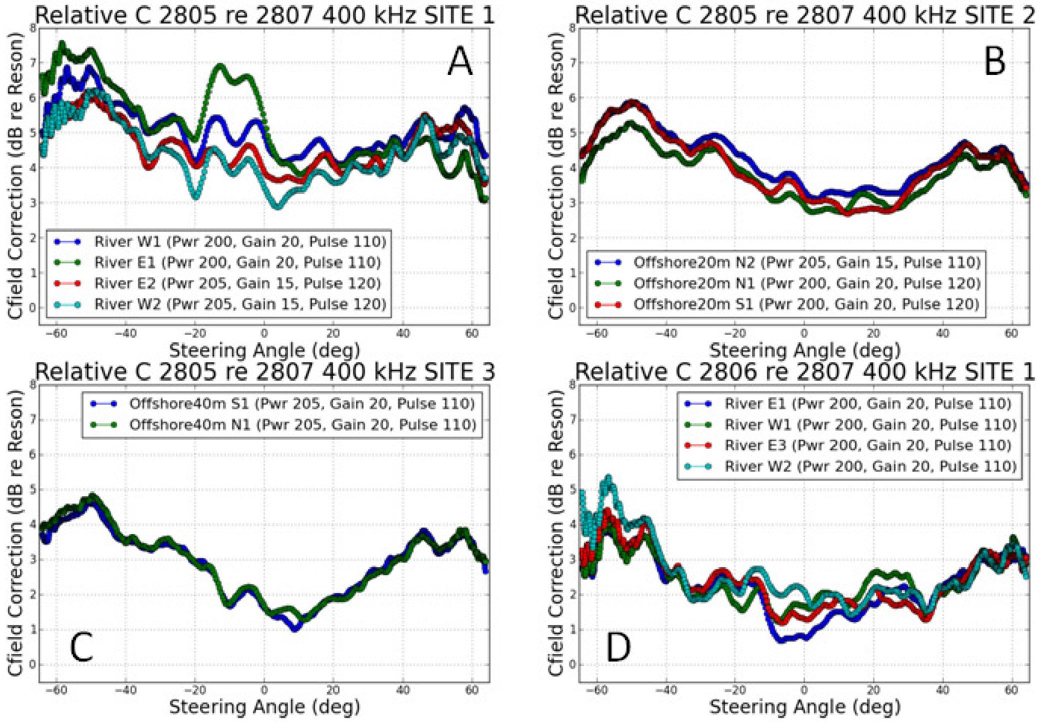


Figure 6: Relative 400-kHz $C_{field}(\theta_s)$ for Launch 2805 system at Site 1 (A), Site 2 (B), Site 3 (C) and for Launch 2806 system at Site 3 (D) relative to the pivot settings used.

With the exception of the 400-kHz E1 line at Site 1 (Figure 6A), the results show similar beam patterns from calibration to calibration for each system and each frequency. However, each frequency and system has its own unique beam pattern. The vertical offsets on the order of 0.5 - 2 dB between calibrations are the result of using different pivot settings (most prominently observed in Figure 5A). The differences between calibrations are on the order of a few tenths of a dB or less when the same settings are used with the exception of the 200-kHz-E2 calibration for the Launch 2806 system at Site 1 (Figure 5D), which is considered an anomaly that requires further investigation. The Launch 2806 system results at Site 1 show slightly higher variation for both frequencies even though the same settings were used multiple times. The smoothest beam pattern (Site 2) comes from the survey lines with the most number of pings (~2000).

The same *inter* calibration files were also processed as relative absolute *inter* calibrations, meaning that the tank calibration corrections were used to process the data from the Launch 2807 system. Figure 7 shows the 200-kHz and Figure 8 shows the 400-kHz relative absolute calibrations at all three sites for the Launch 2805 system (A, B, C) and at Site 1 for the Launch 2806 system (D).

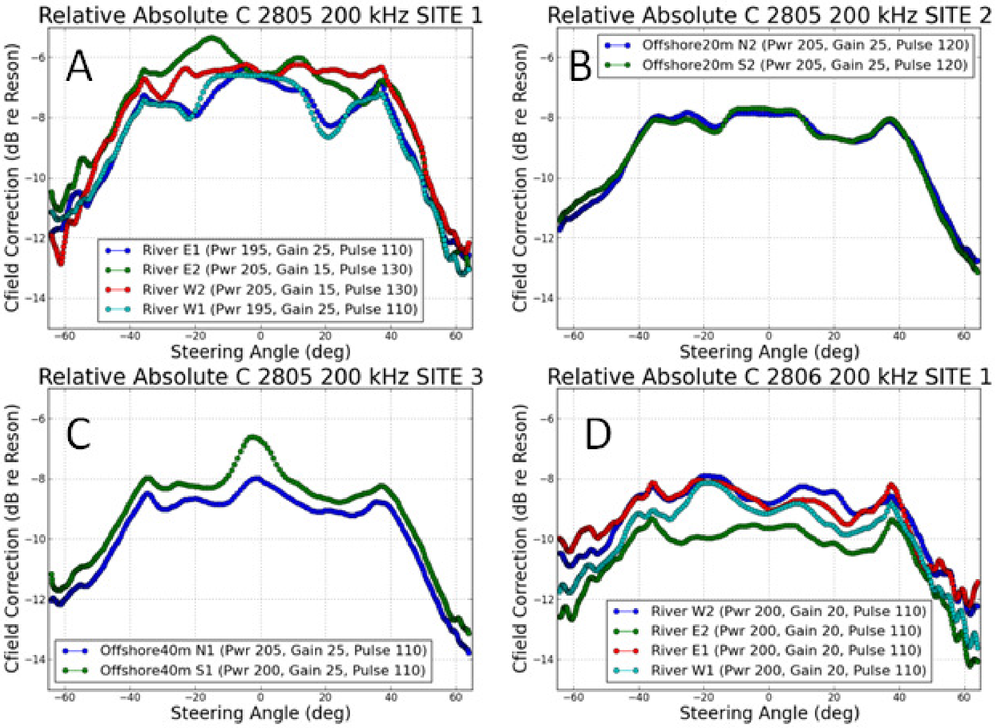


Figure 7: Relative absolute 200- kHz $C_{field}(\theta_s)$ for Launch 2805 system at Site 1 (A), Site 2 (B), Site 3 (C) and for Launch 2806 system at Site 3 (D) relative to the pivot settings used.

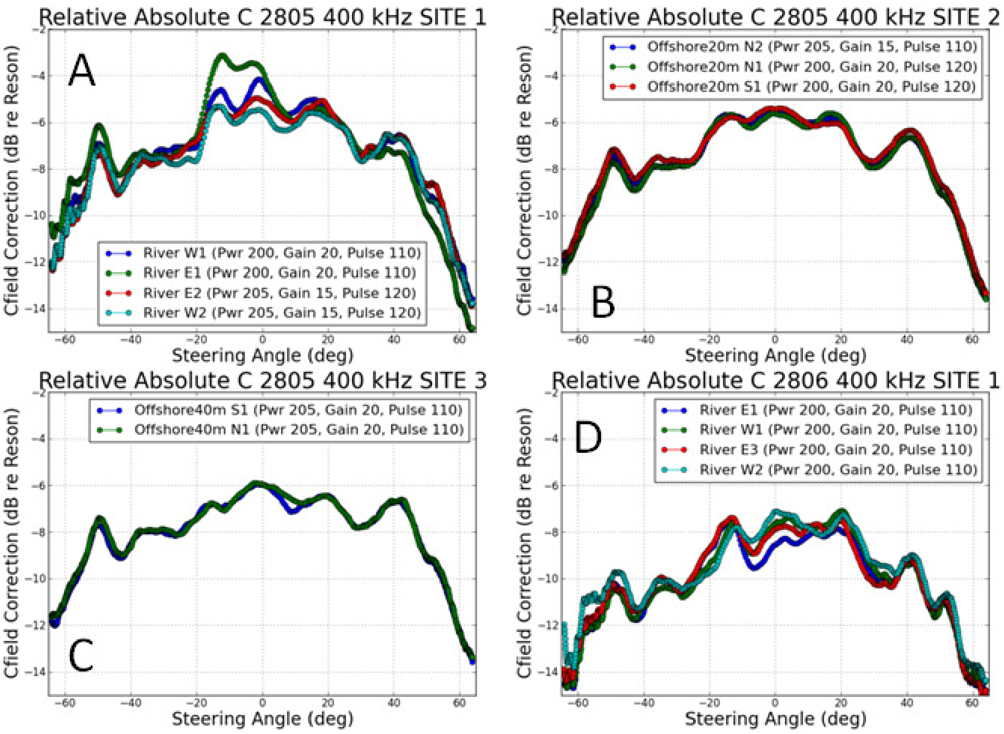


Figure 8: Relative absolute 400-kHz $C_{field}(\theta_s)$ for Launch 2805 system at Site 1 (A), Site 2 (B), Site 3 (C) and for Launch 2806 system at Site 3 (D) relative to the pivot settings used.

The two primary differences between the relative and the relative absolute *inter* calibrations are the shape of the beam patterns and the overall absolute values of the results. The comparative difference in the shape of the beam patterns comes from applying $C_{tank}(\theta_s)$, $\psi_{tx-tank}$, $\psi_{rx-tank}$ to the calibrated Launch 2807 system data. The comparative difference in absolute value (1-5 dB for the relative calibration and an 8-10 dB difference for the relative absolute calibration) comes from applying $C_{tank}(\theta_s)$, SL_{tank}, and G_{tank} to Launch 2807 system data. The high frequency undulating pattern in the outer beams are possible justification for additional smoothing to avoid along track banding artifacts in mosaics.

Intra Calibration (SL_{field}, G_{field}, pseudo PL_{field})

A complete *intra* calibration using the full range of system settings was repeated twice while the launches were moored alongside the NOAA small boat pier on JD242 and JD249 (Figure 3). On JD242 Launch 2805 and Launch 2807 were both moored port-side to the north face of the small boat pier in 7-8 m of water on an ebbing tide. On JD249 Launch 2805 and Launch 2807 were moored in the opposite orientation in similar conditions (starboard-side to the north face of the pier in 7-8 m of water on an ebbing tide) and Launch 2806 was moored port side-to on the south face of the pier in 4-5 m of water. The pier pilings are spaced approximately every 6 m on the north face with additional pilings several meters away from the pier as well, making it impossible to orient the launches such that pilings are not detected by the MBES. The gain setting step intervals were 3 dB on JD242 and 6 dB on JD249. The pulse length setting intervals were 10 µs JD242 and 20 µs JD249. The power setting intervals were always kept at 5 dB. The *intra* calibration was also conducted underway with Launch 2807 near Site 1 in the Yaquina River, and at Site 2 offshore (200 kHz only). The high-end setting values were not used at Site 1 and Site 2 because the systems saturate at high-end setting values in shallow water.

The setting SL_{field}, and G_{field}, and pseudo PL$_{\text{field}}$ tables were created using all the sets of pivot settings used during the *inter* calibrations. Figure 9, Figure 10, and Figure 11 respectively show the 200-kHz *intra* calibration results. Figure 12, Figure 13, and Figure 14 respectively show the 400-kHz *intra* calibration results.

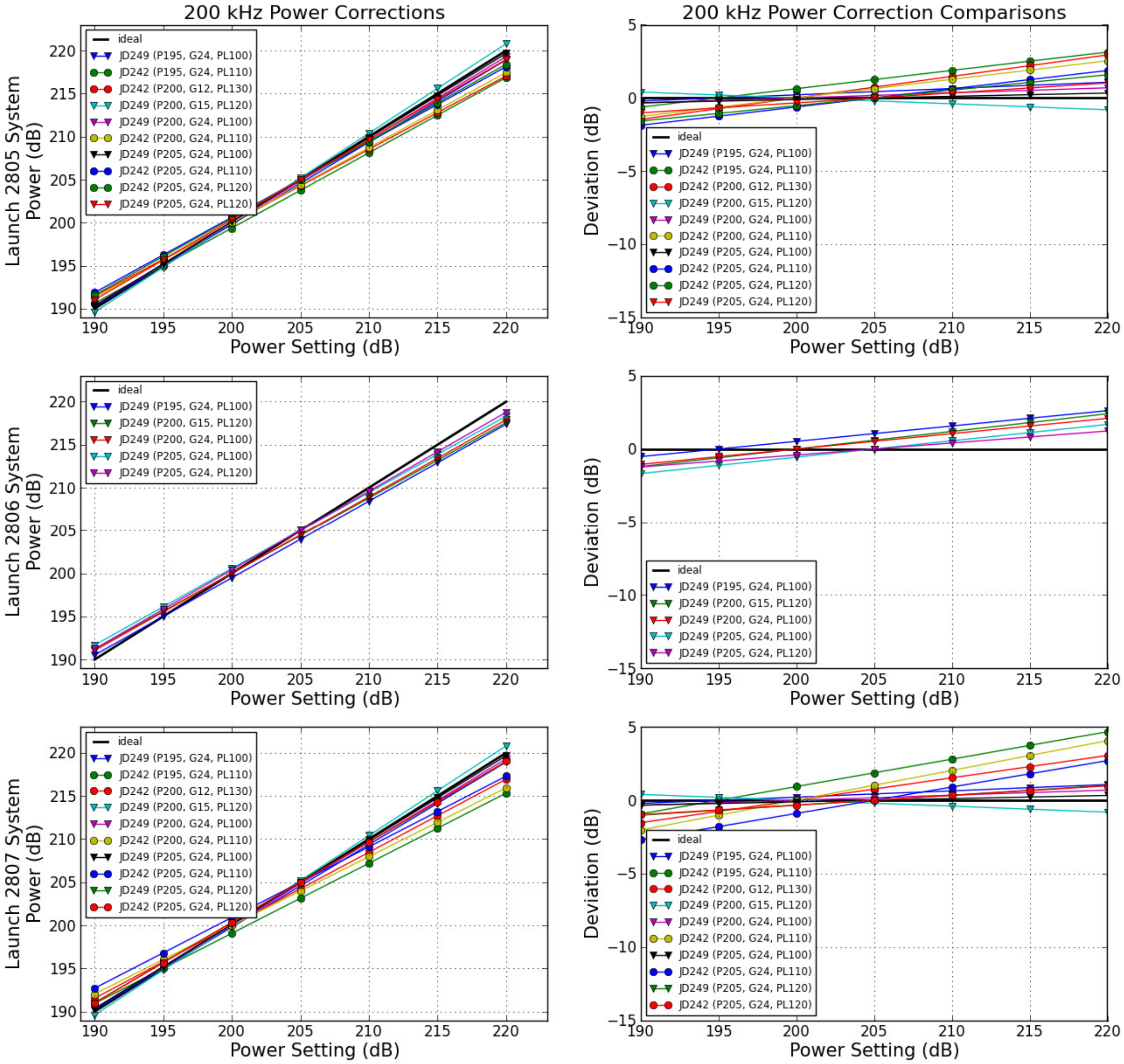


Figure 9: 200-kHz SL_{field} corrections for the systems on 2805 (top), 2806 (middle), and 2807 (bottom). LUTs are plotted on the left, and deviations from ideal are plotted on the right.

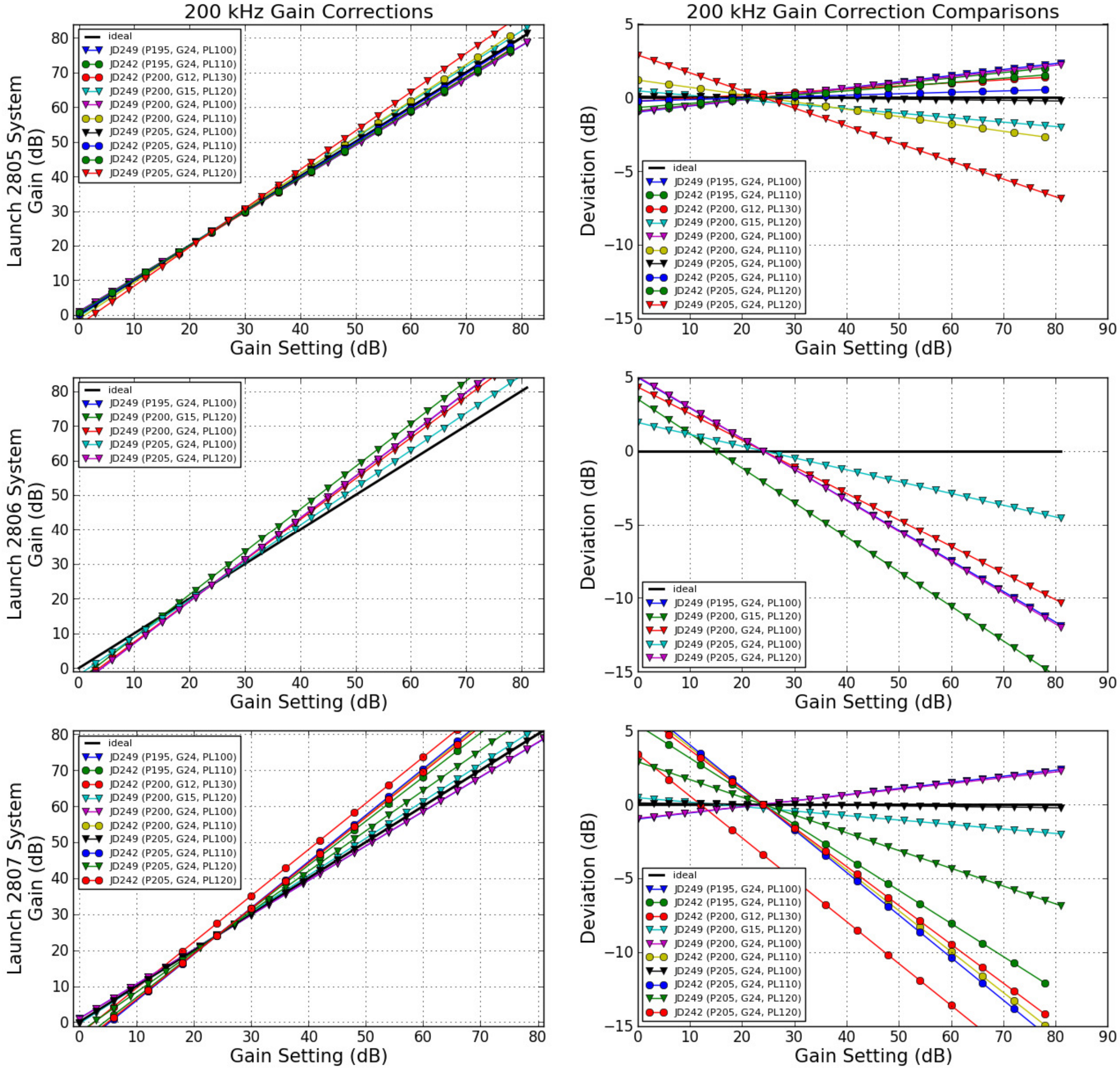


Figure 10: 200-kHz G_{field} corrections for the systems on 2805 (top), 2806 (middle), and 2807 (bottom). LUTs are plotted on the left, and deviations from ideal are plotted on the right.

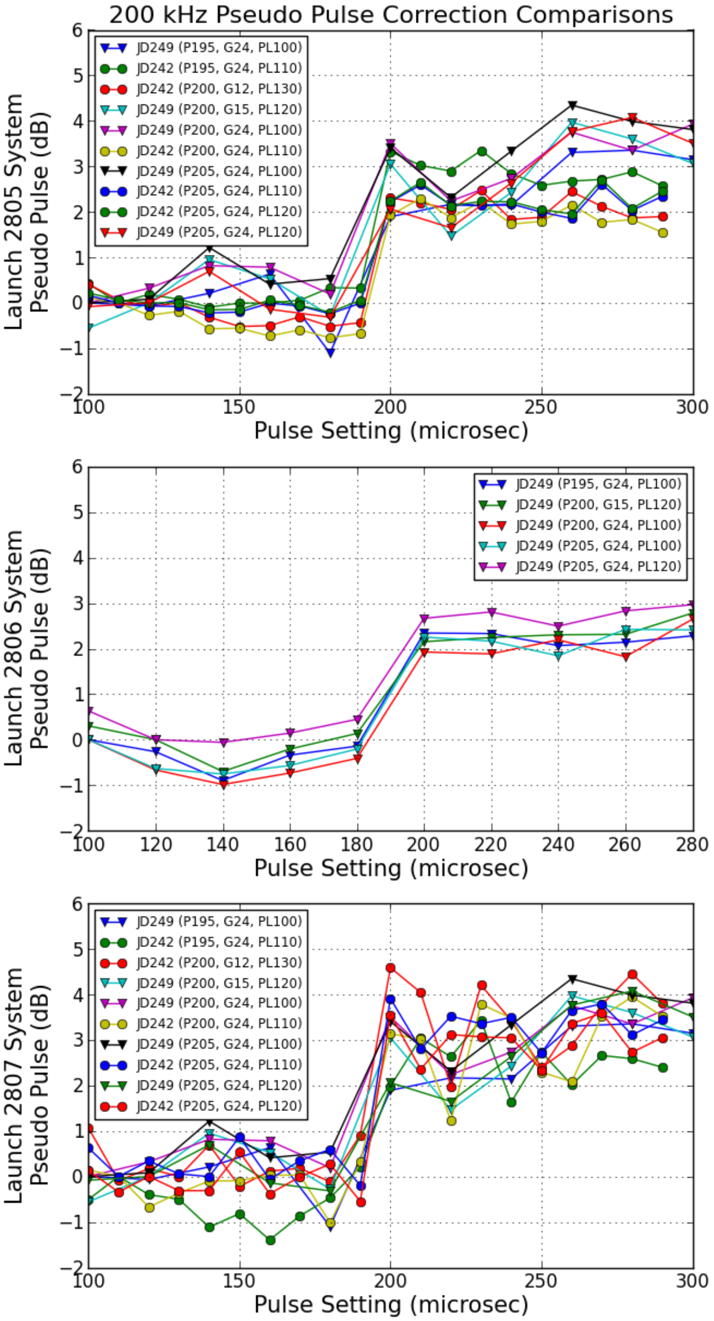


Figure 11: 200-kHz pseudo PL_{field} corrections for the systems on 2805 (top), 2806 (middle), and 2807 (bottom).

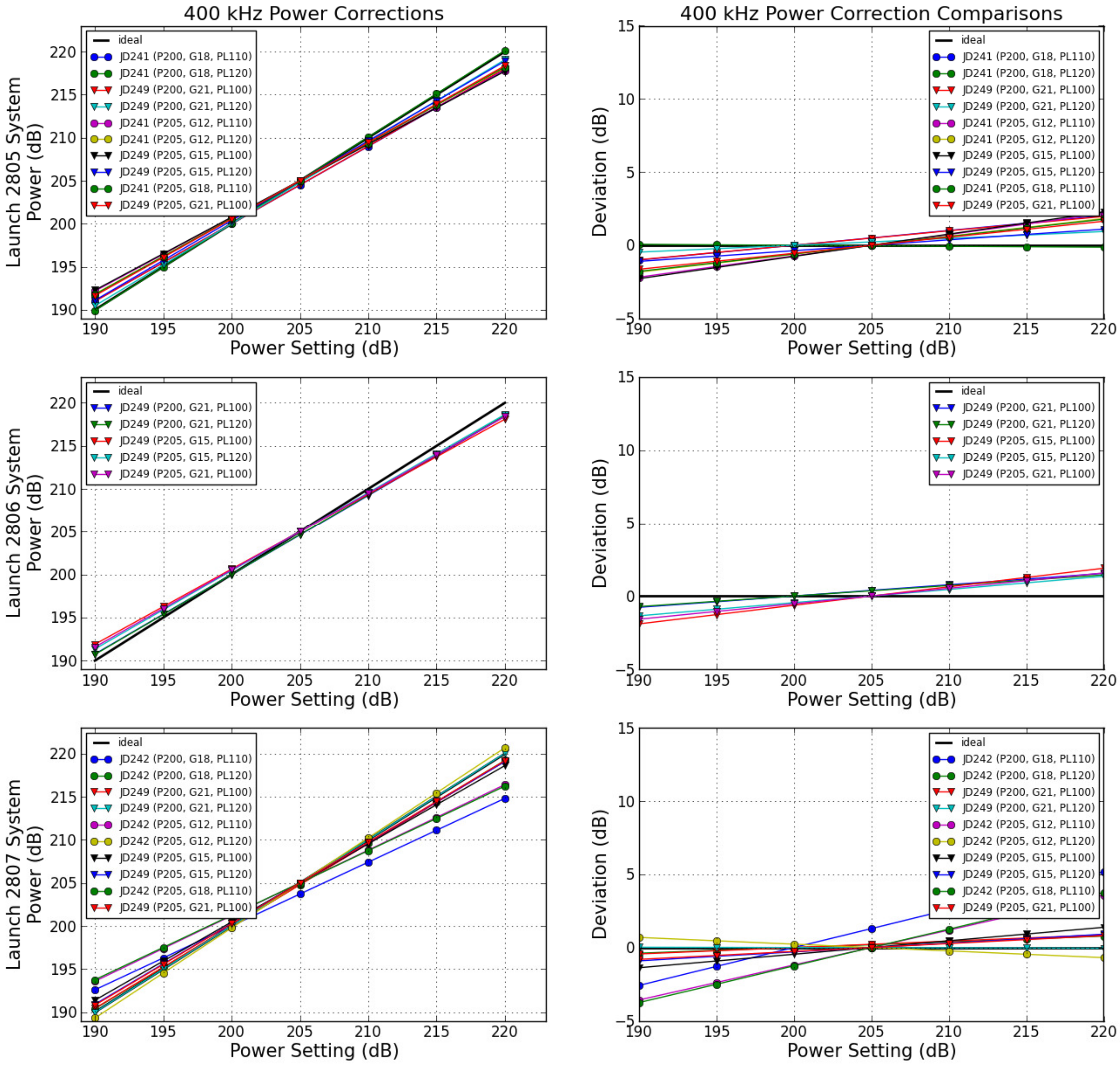


Figure 12: 400-kHz SL_{field} corrections for the systems on 2805 (top), 2806 (middle), and 2807 (bottom). LUTs are plotted on the left, and deviations from ideal are plotted on the right.

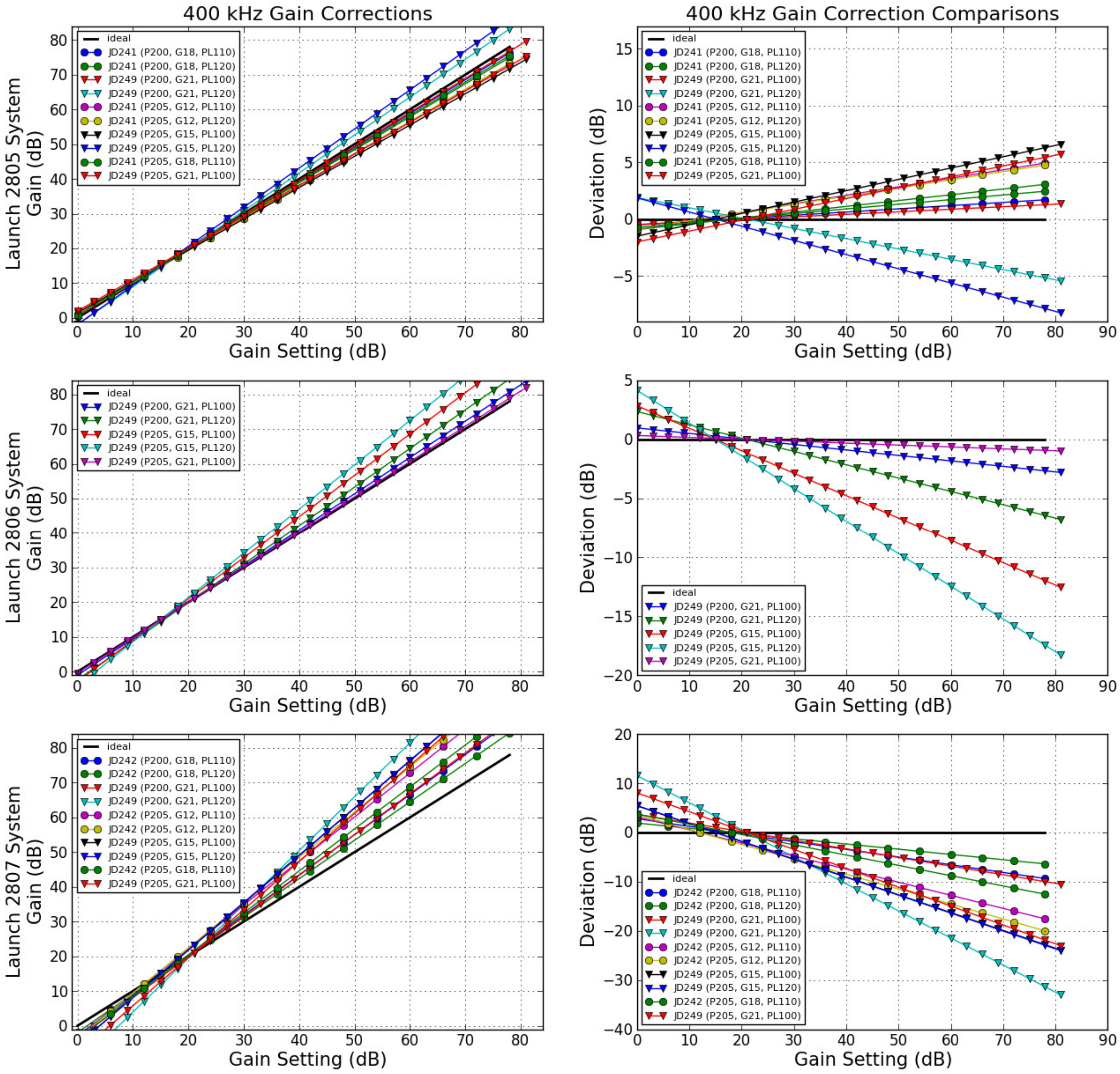


Figure 13: 400-kHz G_{field} corrections for the systems on 2805 (top), 2806 (middle), and 2807 (bottom). LUTs are plotted on the left, and deviation from ideal are plotted on the right.

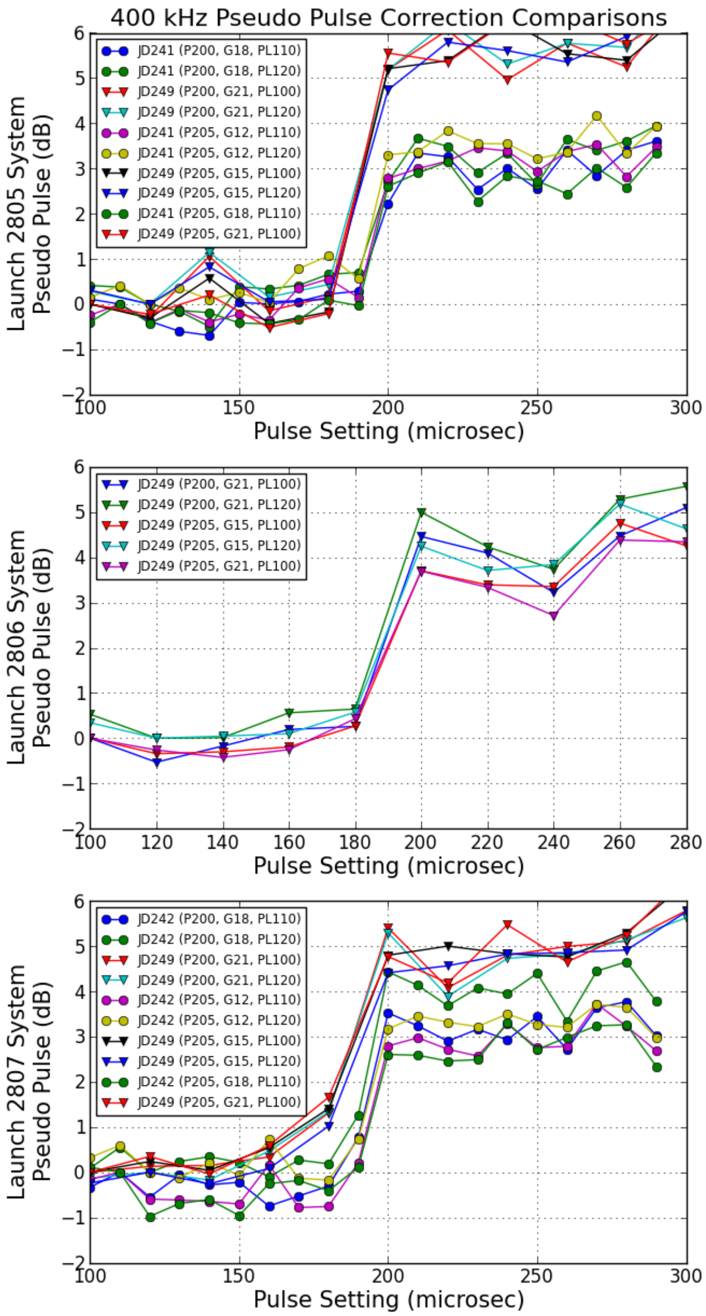


Figure 14: 400-kHz pseudo PL_{field} corrections for the systems on 2805 (top), 2806 (middle), and 2807 (bottom).

All three systems respond similarly to all three settings. The slopes of the G_{field} calibrations are primarily above unity, and the slopes of the SL_{field} are slightly below unity. However, the G_{field} calibrations are much less consistent than SL_{field}, so much so that it is questionable whether or not they are resolvable with any amount of fidelity in the field. Though the general trend of the slopes is similar, the corrections at the high and low-end settings can be many dB, particularly with gain.

The amplitude of the pulse drops at pulse length settings above 200 µs, resulting in pseudo PL_{field} corrections on the order of 3–5 dB for pulse length settings above 200 µs when the pivot setting is below 200 µs. If the pivot settings had been above 200 µs the corrections below 200 µs would have been negative corrections on the order of 3-5 dB. It was also observed that the pseudo corrections above 200 µs vary by 2 dB between JD242 and JD249.

Application of Field Calibration Data to California Survey Data

The primary goal of this work is to develop a set of calibrations that can be used during processing that will result in consistent backscatter measurements for all systems for all operating settings. For this reason the $C_{field}(\theta_s)$, SL_{field}, and G_{field} tables were applied to data selected from a traditional hydrographic survey conducted by *Fairweather* near Los Angeles, California, several weeks after the field calibration data were acquired. The pseudo PL corrections were not applied to the survey data because the pulse length settings used to acquire the data were less than 100 µs. (Pseudo PL corrections were not derived for settings below 100 µs because sonar response was shown to be non-linear in the tank below that value.) The 200-kHz field calibration sets could not be tested as 200-kHz data was not collected in California by the field calibrated launches.

Adjacent survey line files collected by Launch 2805 and Launch 2807 were selected from NOAA hydrographic survey H12620 for use in evaluating how well the *inter* and *intra* calibrations improve backscatter measurement consistency. Figure 15 shows the navigation lines from multiple launches where each field calibrated launch acquired survey data and the location of the two lines used in this case study.

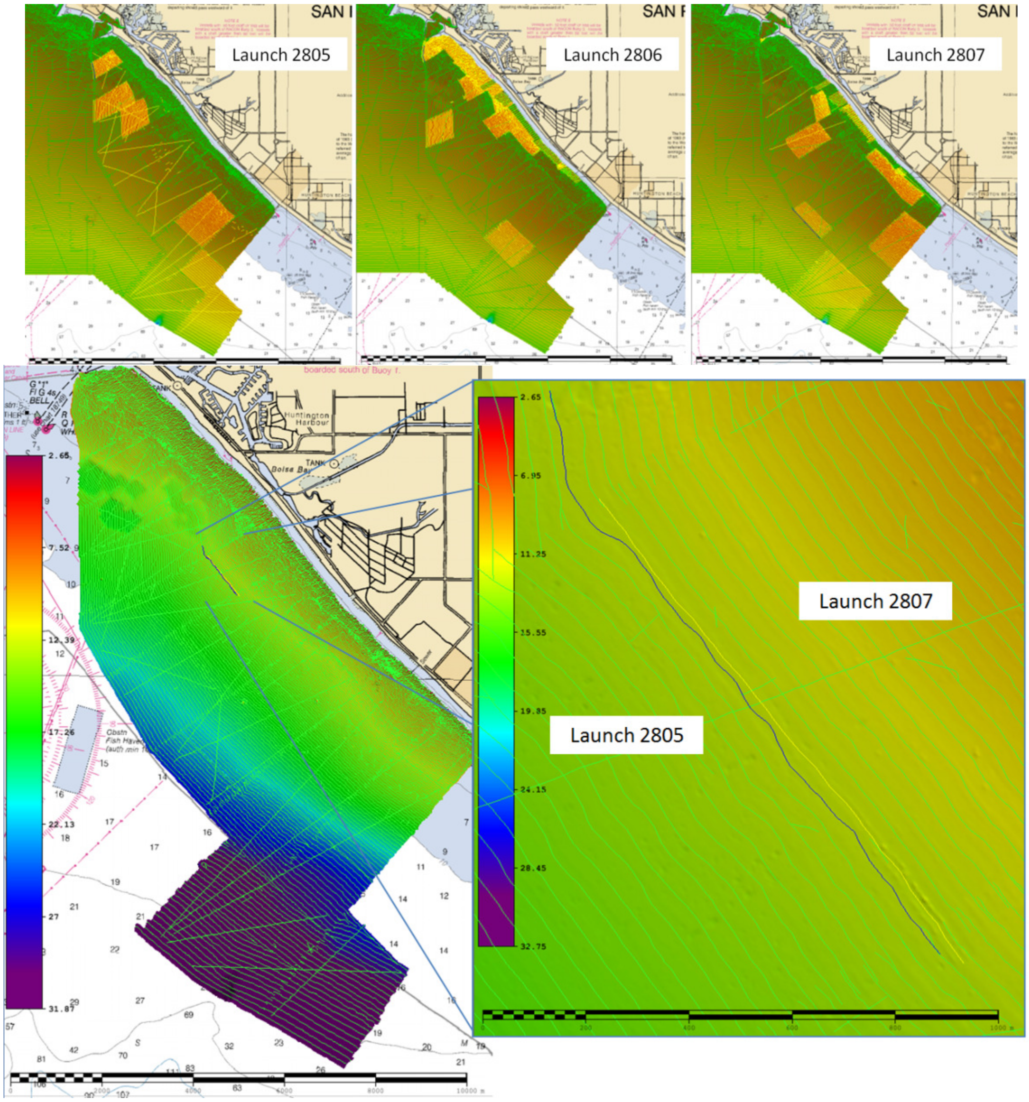


Figure 15: Hydrographic survey H12620 navigation lines segmented by launch.

Figure 16 and Figure 17 depict two adjacent survey lines acquired by Launch 2805 system and Launch 2807 system as processed in FMGT (Figure 16) and with the processing method described to calculate S_b (Figure 17). As observed in Newport, there is an approximate 4-5 dB difference between the two systems, which serves as an example of the initial problem this work seeks to address. The Launch 2805 system was operated with a single set of settings throughout the duration of the line (power = 199, gain = 39, pulse = 50 µs), while the Launch 2807 system was operated using a variety of setting changes (power ranging from 205 to 220, gain ranging from 15 to 25, and a pulse length ranging from 50 to 80 µs). The nominal settings have been used for processing without any corrections applied.

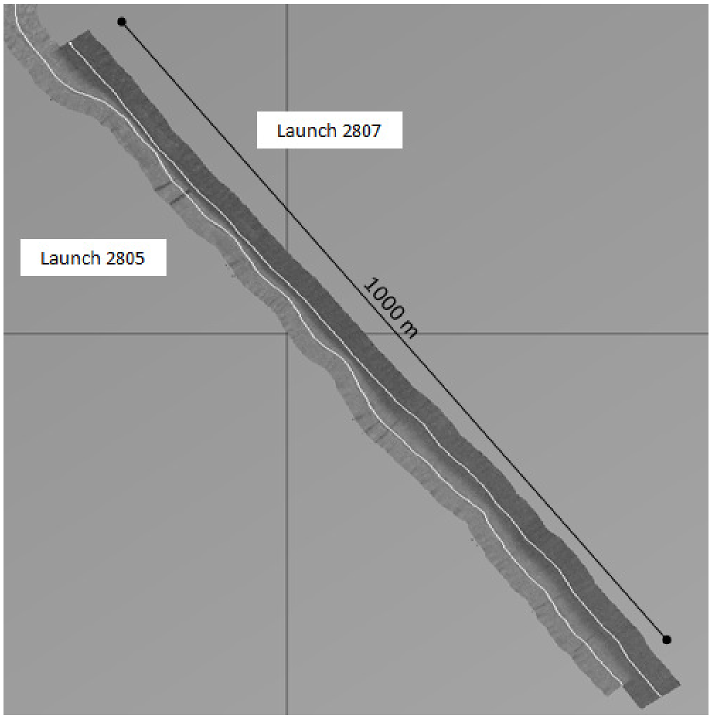


Figure 16: Two adjacent lines run by Launch 2805 (mode: 30.5 dB) and Launch 2807 (mode: 35.7 dB) as processed and mosaiced in commercial software, FMGT (default color map, -70 to 10).

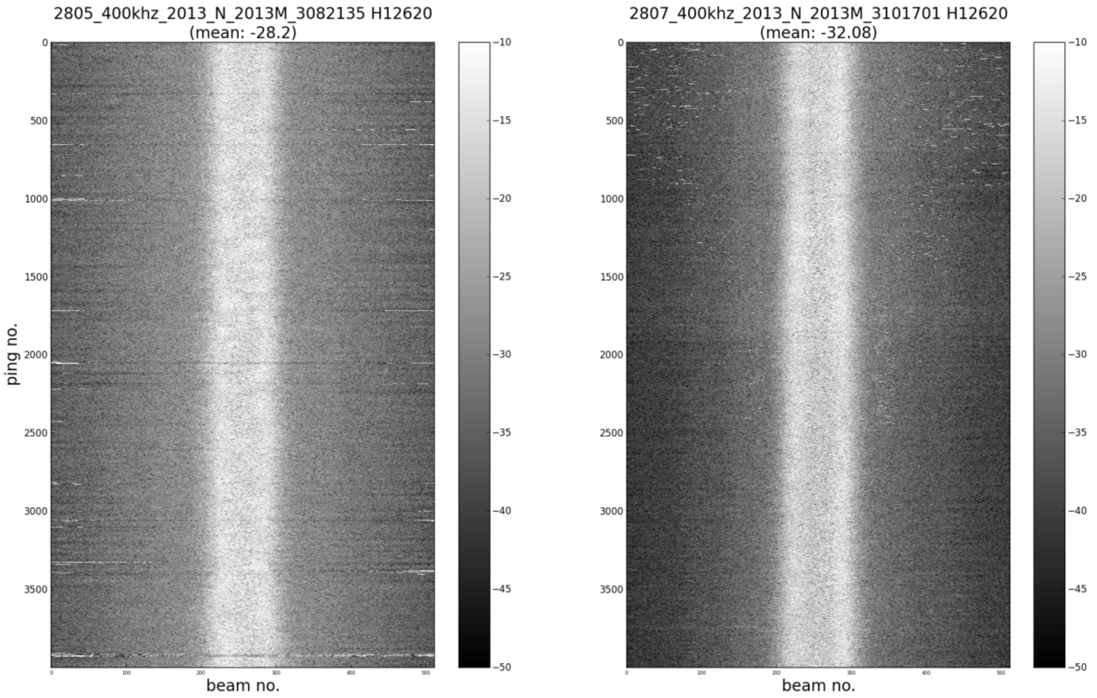


Figure 17: The same two lines shown in Figure 16 processed with research code without any field or tank calibrations applied to either file.

The mode of the normalized histogram in FMGT of the data acquired by the launch 2805 system is -30.5 dB, and for the launch 2807 system it is -35.7 dB (a 5.2 dB difference). The mean of the beam means for the launch 2805 system data processed in the research code is -28.20 dB, and for the launch 2807 system it is -32.08 dB (a 3.9 dB difference). Figure 18 shows the results of applying the five relative absolute *inter* calibrations from all sites in Newport with their associated *intra* calibrations. In this case $C_{tank}(\theta_s)$, SL_{tank}, and G_{tank} $\psi_{\text{tx-tank}}$, $\psi_{\text{rx-tank}}$ have been applied to the Launch 2807 system data file, and $C_{field}(\theta_s)$, SL_{field}, and G_{field} have been applied to the Launch 2805 system data file.

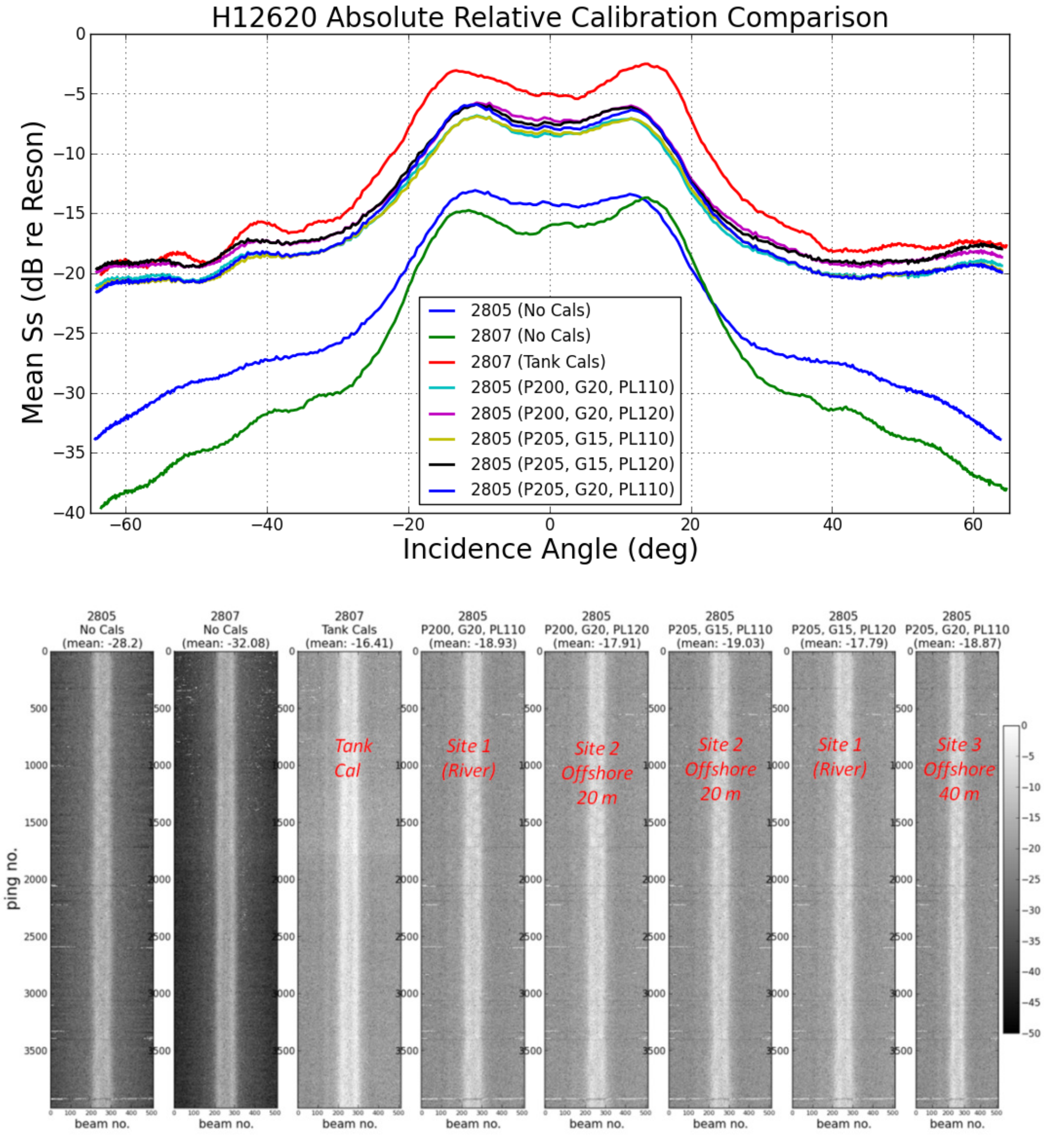


Figure 18: Launch 2805 and Launch 2807 system data processed without any calibration corrections, and Launch 2805 system data processed with five relative absolute field calibration sets and without any calibrations: beam averages (top), mosaics (bottom).

The blue and green beam means for the systems on both launches do not have any calibrations applied (i.e. the initial case of doing nothing). The remaining colors show the result of applying the five realizations of the *inter* and *intra* field calibration sets acquired in Newport, OR. In this case $C_{tank}(\theta_s)$, SL_{tank}, and G_{tank} $\psi_{\text{tx-tank}}$, $\psi_{\text{rx-tank}}$ have been applied to the Launch 2807 system data file, and $C_{field}(\theta_s)$, SL_{field}, and G_{field} have been applied to the Launch 2805 system data file. Though the field calibrations bring the Launch 2805 system data closer to the Launch 2807 system data, variation between calibrations is on the order of 1-2 dB, likely due to the variability between their associated *intra* calibrations.

Discussion

The application of $C_{field}(\theta_s)$, with its associated SL_{field}, and G_{field} to hydrographic survey field data from California provides evidence that a beam-to-beam full swath difference can reduce backscatter measurement inconsistency to within a dB or so (Figure 18). This implies that if systems are initially inconsistent by more than 1 to 2 dB, then this correction is worthwhile. If systems are initially inconsistent by less than 1-2 dB then there is little added benefit of applying the *inter* calibration results unless the field procedure can be refined.

The *intra* calibration may still be necessary if the slopes of the system responses about the same pivot settings are significantly different. It is inherently implied that if data from systems with different *intra* calibration slopes are acquired using the full range of settings (and are not corrected), then the combined backscatter data will be inconsistent. Careful attention should be paid to which calibrations are being applied and with what they are paired with to avoid introducing beam pattern artifacts or incorrectly applying corrections to the various system parameters. The general across-swath beam pattern between systems appears consistent between sites. However, the pattern appears less consistent near nadir and in the outer beams. Further smoothing and/or exclusive use of select regions of greater stability within the swath should also be considered.

Inter **Calibration** (C_{field},)

The primary value of referencing all systems to the tank calibrated system is that in addition to theoretically resulting in more consistent measurements between systems, all measurements are closer to absolute backscatter estimates. Considering that $C_{default}$ is approximately off by 6 dB for 200 kHz and 9 dB for 400 kHz this is a significant enhancement. Although acoustic seafloor backscattering models developed by Mourad and Jackson have not been developed for 200- and 400-kHz frequencies yet, Figure 19 shows that using the tank calibrations results in backscatter estimates that are much closer to those predicted by the 100-kHz models presented in the University of Washington Applied Physics Lab's Ocean Environmental Acoustic Models Handbook (APL-UW, 1994), based on (Mourad and Jackson, 1989).

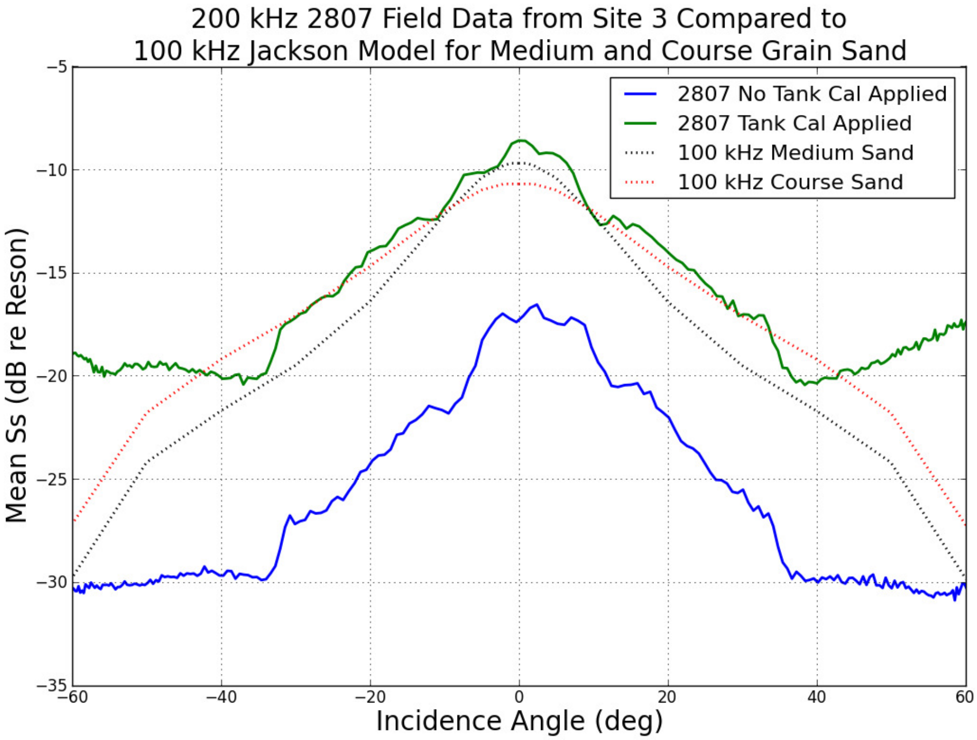


Figure 19: Beam averages from tank calibrated system, Launch 2807, at Site 3 with and without tank calibrations applied compared to 100 kHz Jackson models for medium and course sand.

However, applying tank calibration corrections have the potential to introduce beam pattern artifacts from $C_{tank}(\theta_s)$, $\psi_{\mathrm{tx-tank}}$, and $\psi_{\mathrm{rx-tank}}$, and systematic biases from applying SL_{tank} and G_{tank} to the reference system itself and all other systems referenced to it if the original tank calibration is inaccurate. A possible compromise between these two methods might be to change $C_{default}$ to a single representative value of the tank calibration such as the mean over a stable range of incidence angles, and pursue relative calibrations, thereby eliminating the introduction of beam pattern artifacts. Another option to consider is a single value calibration for all steering angles. The field calibration as proposed works well for oblique angles, but not as well for near nadir beams or extreme outer beams. Certainly further investigation of how accurate and stable each term is for both the tank and field calibrations and at which range of angles is warranted.

Intra Calibration (SL_{field}, G_{field})

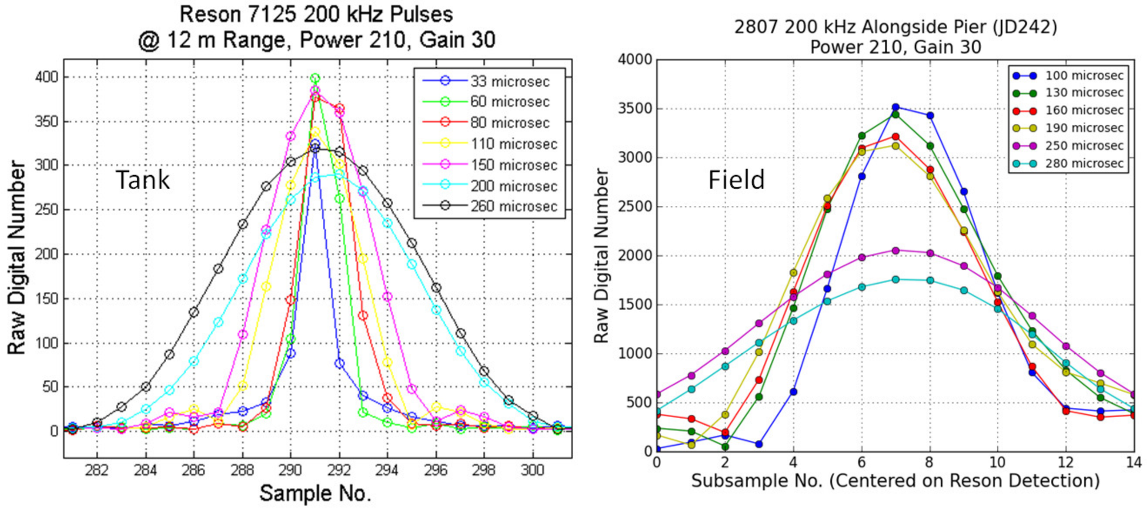
The results of the *intra* calibration show that the slopes of the system responses to gain and power setting changes are not unity (as was observed in the tank as well) and therefore must be considered to achieve consistent backscatter measurements for all setting combinations. However, the variation between the *intra* calibrations is so wide, particularly for the gain settings, that perhaps the *intra* setting responses are not resolvable in the field. Further investigation into the cause of the variation between calibrations is necessary, particularly into the raw water column amplitude records and how the data are being treated by the processing approach which itself may very well be introducing these inconsistent results. Additional work is necessary to more carefully define the linear region of the system response about the pivot setting.

Considering the slopes of the SL_{field} and G_{field}calibrations relative to each other provides an indication of how much each correction will contribute to backscatter measurement consistency. For slopes other than unity, the magnitude of the backscatter measurement inconsistencies grow as settings further away from the pivot settings are used to operate the MBES. If the slopes of SL_{field} and $G_{field}$are unity, then their use does not contribute to consistent backscatter measurements since the correction line always passes through the pivot setting. Furthermore, if the slopes of the SL_{field} and $G_{field}$for both the field calibrated system and reference system are the same, then the backscatter measurements for both systems will remain consistent for any settings used during MBES operation. The further the slopes of the SL_{field} and G_{field} LUTs are away from unity and the further the setting is away from the pivot setting, the greater the importance of correcting for them. Significant deviations from unity are cause for further investigation into the results of the test, and call into question the processing method, the conditions in which the test was conducted, and/or the general performance of the MBES.

Pulse Length Calibration, pseudo PL_{field}

The MBES system responses to pulse length setting changes that were reported by Lanzoni (2012) and also observed in the *intra* calibration field data are unusual in that higher amplitudes at pulse lengths below 200 μs are observed. The implication is that when systems are operated with pulse length settings both above and below 200 μs, regardless of how the amplitude records are sampled, inconsistent backscatter measurements on the order of 2-5 dB are expected as has been observed (Figure 11 and Figure 14). For this reason the pseudo PL correction has been proposed.

Looking more closely at the amplitude records from both the tank and field data around the target detections using different pulse length settings suggests the relationship between pulse length and amplitude might be related to the data sampling rate. Figure 20 shows the nadir beam pulses recorded in the test tank at UNH, and in the field mounted on Launch 2807 alongside the pier using the same power and gain settings with different pulse length settings. The pulses from the tank data were generated by the calibration hydrophone (TC 4034) at a range of 12 m, and received and recorded by the tank-calibrated MBES. The pulses from the field data were transmitted and received by the same MBES mounted on Launch 2807 while alongside the NOAA pier in Newport, Oregon (15 amplitude samples centered about the seafloor detection were recorded). Higher amplitudes with shorter pulse lengths are observed in both cases. While each record of every beam and ping is unique, this plot shows the general tendency of the system response to different pulse length settings that were observed both in the tank and in the field for all systems and frequencies. The opposite effect (lower amplitude with shorter pulse lengths) was observed by a Reson 8125 (Parnum and Gavrilov, 2012).


Reson 7125 200 kHz Pulses @ 12 m Range, Power 210, Gain 30

2807 200 kHz Alongside Pier (JD242) Power 210, Gain 30

Figure 20: Recorded pulses of the nadir beam of the tank calibrated MBES in the tank (left) and in the field on Launch 2807 (right) using different pulse length settings.

The digital recording interval of the Reson 7125 is 29 µs. This implies that pulses generated with the lowest pulse length setting of 33 µs will be represented by one to two samples, which is consistent with what is observed in the recorded data from the tank calibrations. The causes or reasons for higher amplitudes with shorter pulse lengths have not been further investigated or understood. This work goes only so far as to show the system response to different pulse length settings, and to propose a way to account for it in the backscatter reduction process in the form of a pseudo PL correction.

Conclusions

Four unique MBES-vessel pairings were observed to produce backscatter measurements with inconsistencies as low as a few tenths of a dB and as much as 5-7.5 dB in a fairly controlled field environment. A field calibration method was developed to produce *inter* and *intra* corrections relative to a single set of operational settings (power, gain, and pulse length) and to a single reference system that itself can either be used to produce absolute backscatter estimates by applying its tank calibration corrections to the data it records, or its own uncorrected backscatter estimates. The method was tested in a challenging location with reasonable results. The *inter* and *intra* corrections can be used as a full set (or as a subset if some calibrations are deemed unnecessary) for any setting combination to reduce inconsistencies to within a dB or so. This procedure informs when applying $C, SL, G,$ and pseudo PL corrections is worthwhile. This study has also explored alternate approaches for deriving and applying C.

Finally, the development and implementation of tools in commercial software are necessary to 1) handle the application and meta data associated with both tank and field calibration corrections; 2) check that all the underlying assumptions to use DN differences are met and/or to make careful corrections for S_b beam-to-beam or incidence-angle-to-incidence-angle differences to create $C_{field}(\theta_s)$ for a set of pivot settings; and 3) create corrections for MBES responses at other operational settings. Comparative checks should include the before and after CTDs, the noise in the water column, the vessel attitude spectral densities, the beam to beam distributions, beam noise floors, and across-swath beam pattern shape for both systems. If any of these are not sufficiently similar, then corrections must be made to account for them. Most important is the ability for users to apply radiometric calibration corrections in commercial software in any appropriate way they choose, specifically $C(\theta_s)$, SL(power setting), G(gain setting), $\psi_{tx}(\theta_s)$, $\psi_{rx}(\theta_s)$, τ(pulse length setting), or pseudo corrections such as that proposed for pulse length settings or possibly for beam pattern or MBES reference frame misalignment. Meta data to track the reference system and its level of calibration, the pivot settings or any other operational attribute combined in the field calibration output, and any other parameterized setting corrections

Overall this work quantified the problem of backscatter measurement inconsistency between four Reson 7125 SV1s, and developed a balanced alternative to absolute tank calibration for all MBES. The method is an efficient compromise in terms of equipment, time, and expertise to relatively calibrate any number of systems to a single tank calibrated system. Although additional refinements are necessary, this work lays a foundation for achieving consistent backscatter measurements from many systems. As MBES data acquisition and processing techniques improve and the large-scale use of quality backscatter data increases, seamless backscatter products from multiple systems will remove the barriers to large-scale automated seafloor characterization.

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