

A Single Vessel Approach to Inter-Vessel Normalization of Seafloor Backscatter Data

LT Samuel Greenaway

NOAA Ship *Ferdinand R. Hassler*, U.S. Department of Commerce, 439 West York Street, Norfolk, VA 23510,
samuel.greenaway@noaa.gov

Glen Rice

NOAA Integrated Ocean and Coastal Mapping Center, 24 Colovos Road, Durham, NH 03824, glen.rice@noaa.gov

Abstract

Integration of backscatter data from multiple un-calibrated echosounders remains a challenge. The arbitrary offsets that are acceptable within a single sensor application become problematic when integrating multiple sensors into a common data set. Instruments typically have differences in overall sensitivities and/ or beam patterns that are large enough to complicate the combination of the individual sensor data sets into a coherent, project wide product.

The dual-head Reson 7125 installation on the NOAA Ship *Ferdinand R. Hassler* is useful intermediate step between a single instrument installation and a true multi-vessel application. When operated simultaneously, the temporal variation in the acoustic properties of the seafloor and the water column can be eliminated between the two systems.

Using data acquired during production hydrography, we solve for the offsets between the two heads for simultaneously logged data. This approach is then broadened to determine offsets between different days, and then different hardware installations throughout the project. We find that the normalization offsets vary significantly between the heads, between different runs (likely due to the Reson normalization process), and different installed receiver components. Accounting for these offsets, we are able to generate project wide mosaics and backscatter products.

Introduction

Backscatter is useful but the end product, and thus the processing paradigm, is dependent on the application. Ideally backscatter would be from fully calibrated echosounders so the measured backscatter reflected only the characteristics of the seafloor and not the instrument used to acquire it (de Moustier and Matsumoto 1993). While calibration has been done in both a test-tank environment (e.g. Foote, et al 2005 and Lanzoni et al. 2009) and in the field for deployed systems (e.g. Ona et al 2009), effective field calibration of deployed multi-beam systems remains elusive. As a result of this lack of calibration, many of the techniques that have been developed for interpreting backscatter data, such as the Angle Range Analysis approach (Fonseca and Mayer 2007), or the Bayesian approach of Simons and Snellen (2008) do not rely on absolute backscatter values for segmentation and classification. These and other techniques rely on relative signals, either across a swath in the ARA case, or in the shape of the

measured distribution. Because all the comparisons are relative, these methods can accommodate the arbitrary offsets introduced by the lack of accurate calibration parameters. Much of the work that has been done with backscatter is from single platforms and short duration data sets. In these cases, the arbitrary calibration offsets can reasonably be assumed to be constant throughout the data set. This convenient assumption can no longer be relied on when multiple vessels are involved with the survey or the survey extends over a significant portion of time. For production hydrographic survey work by NOAA's fleet, up to six individual platforms might be used on a particular survey area and acquisition may span many months. Absent a full calibration of all instruments used, some normalization, or determination of the relative offsets between different instruments, is required if we seek to combine all the backscatter data before applying the segmentation or classification technique, whatever the method. Without this normalization step, any analysis must be done on a vessel-by-vessel basis and combined only in the product stage.

NOAA's newest hydrographic ship, Ferdinand R. Hassler, features a SWATH design and a widely spaced dual-head multibeam system. The calibration offsets of the two heads is not generally known and because the two systems run in parallel, segmentation into contiguous areas for independent processing by vessel is not a viable solution. While this configuration requires a field method for determining the relative offset for creating any useful backscatter products, it also provides an intermediate step to the more general multi-vessel problem. Figure 1 shows an example of one complete survey sheet of data covering approximately 130 km² (38 nm²). These data have been fully processed through CARIS HIPS and IVS FMGT, but no correction for the overall gain offset has been applied between the two heads or between different initializations of the same head. The artifact introduced by the lack of normalization between the systems severely degrades the interpretation of the mosaic.

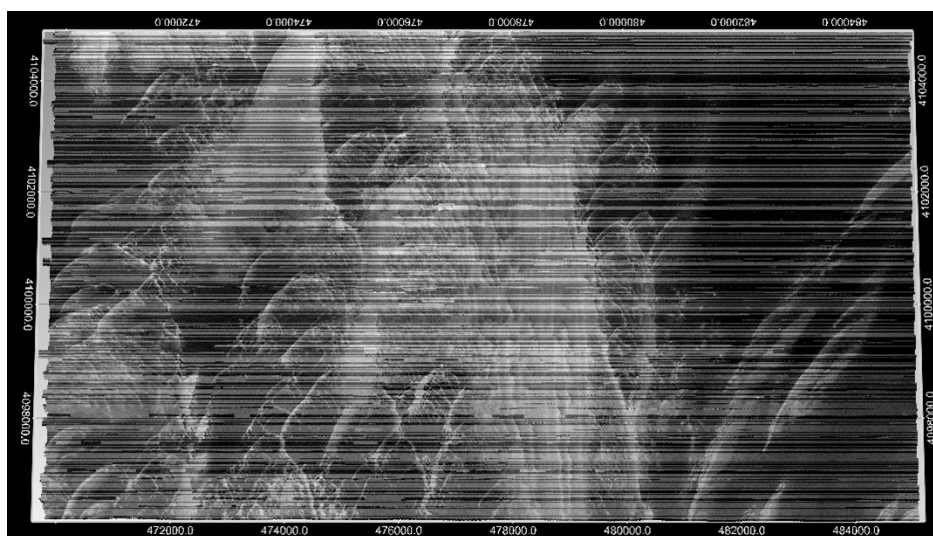


Figure 1: Processed backscatter mosaic with no corrections applied between heads or initializations. While some geological signal can be discerned, the artifacts dominate the image. Bounding box units are in meters

In this paper, we use the dual-head system on Ferdinand R. Hassler to progressively develop methods to determine the relative offsets between any two systems. We start by looking at a small area (four km²) surveyed in a short period of time (6 hrs) with simultaneous coverage by both heads and build to large areas surveyed over many months with different system components. We base this approach on analysis of distributions of backscatter strength. Simons and Snellen (2009) have shown that the distributions of backscatter are useful in segmentation and classification of the seafloor. We create mosaics and then use the distributions of mosaic intensity from different systems to solve for the calibration offsets between systems. By creating mosaics using commercial implementation (QPS FMGeocoder Toolbox) of the Geocoder software (Fonseca and Calder 2005) we approximate radiometric and geometric corrections necessary to eliminate all but the gain offset of the sonar. We do not apply any beam pattern correction, but because this beam pattern effect is removed in ping averaged angle varying gain (AVG) correction, any residual beam pattern effects are lumped into the one static gain offset.

Our approach does not require a particular bottom type, but does require that a common bottom type be present in the areas being compared. This constraint is easily satisfied in the case of concurrent acquisition between two heads on one vessel, but becomes more difficult with two spatially separated survey areas. The case of concurrent acquisition with two echo sounders on one vessel is further simplified because any temporal variability in either the acoustic propagation properties the water column or the properties of the seafloor is eliminated. For this analysis, we do not distinguish the root cause of the overall offset between the systems. The offset could be due to sensitivity differences in either the transmit or receive arrays, static gain offsets in the electronics, or variations in the power supplied to the transmitter.

Previous work (Intelmann et al. 2006) has approached this problem through an image processing perspective. Intelmann created mosaics by vessel and then adjusted the dynamic range and bounding values of the grey-scale images to minimize the visual discontinuity at junctions between vessel survey areas. Our approach is similar, in that we base our analysis on the mosaic and seek to minimize the discontinuity between different vessels and areas. However, we solve for the offsets directly and then reprocess the backscatter data with those correctors applied. This approach should allow for subsequent analysis or segmentation of the entire survey area based on any number of methods, and is not limited to a mosaic or other image based approaches.

Ship Particulars

Ferdinand R. Hassler is a small water-plane twin hull design (SWATH), with a overall length of 37.7 meters, beam of 18.5 meters, draft of 3.8 meters. Two Reson 7125-SV multibeam echosounder systems are installed as a dual head system. The port and starboard systems are mounted in their respective hulls with a 4.5 degree outboard tilt. These systems are located approximately 1/3 of the hull length aft from the bow. The configuration of the ship is shown in Figure 2.

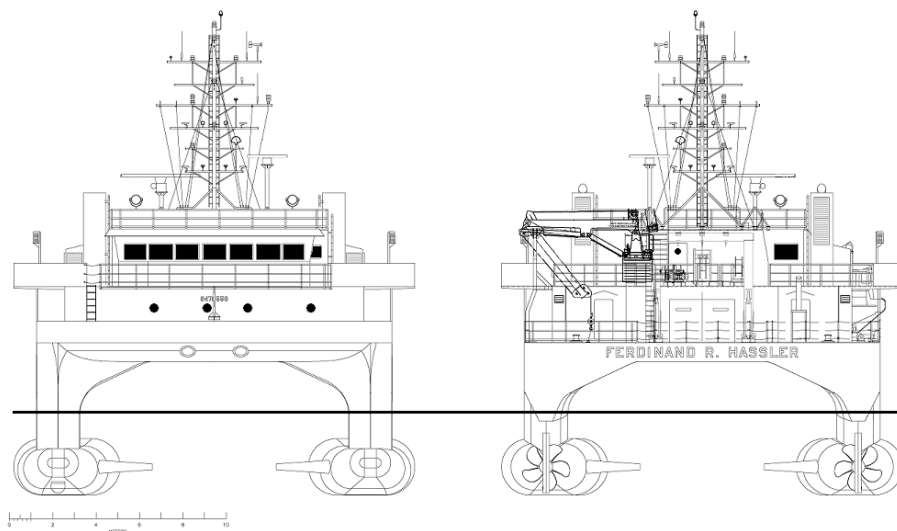


Figure 2: Configurations of *Ferdinand R. Hassler*. Bow and stern view. The Reson 7125 systems discussed in this paper are mounted on the keel of each hull, approximately 1/3 of the hull length back from the bow

Data Acquisition and Processing

All bathymetric and backscatter data for this project were acquired from April to December 2012. The project area is approximately 25-30 nautical miles east of the entrance to Chesapeake Bay. This survey area is divided into six individual survey sheets. The seafloor in this area is comprised largely of fine to medium sand with some broken shell. Depths throughout the survey are ranged from 19 to 35 meters.

The two Reson 7125s are configured to ping simultaneously. Frequency Modulation (FM) and a center frequency offset are used to separate the signals on reception. For most of this project the port head was configured to sweep up in frequency from 416 to 436 kHz and the starboard head was configured to sweep down in frequency from 396 to 376 kHz. For the purposes of this paper we consider the seafloor to have equivalent backscatter characteristics at each of these frequency bands. The echosounders were configured in equidistant ("Best Coverage") beam steering mode. The opening angle of the 7125 systems was configured based on analysis of coverage, speed, and expected sound speed refraction errors for each survey. This angle typically varies between 120 and 140 degrees.

Position and attitude were fed from two Applanix POS v.4 to each Reson unit. The inertial motion unit (IMU) of each POS is located within 2 meters of the sonar head in each hull. Data was logged in the native s7k format with the following records: 1003, position; 1012, roll, pitch, heave; 1013, heading; 7000, 7k sonar settings; 7004, 7k beam geometry; 7006, 7k bathymetric data; 7008, 7k generic water-column data (used for snippet backscatter); and 7503, remote control sonar settings. Bathymetry was processed through CARIS HIPS following established NOAA procedures with correctors applied for water levels, sound velocity correction, and post processed heave. For all processing, the port and starboard MBES are treated as separate vessels.

During data acquisition, operating parameters such as power, gain, and time varied gain were generally left unchanged. Pulse length was set to 1.0 ms.

Backscatter was initially processed through QPS FMGT v7.3.3 using the Reson TVG plug-ins. The backscatter was initially processed on a sheet wide basis for each head and then partitioned by areas of similar response. Figure 3 shows the partitioning of one sheet into segments of similar response. This partitioning was done visually and in consultation with the acquisition logs which recorded restarts of the MBES. In all cases, the intra-head variability was due to different initializations of the MBES. That is, if the MBES was restarted and renormalized, the offset were generally different. Each section of similar lines (ranging from a few lines to many days) was then reprocessed as a stand-alone project. The snippet backscatter logged in the 7008 record was paired with the processed Caris HDGS directories and processed using default parameters. A 1-meter resolution mosaic was generated and exported as ASCII text (mosaic value only). Distributions of the mosaic values were calculated in python. The subsequent analysis operates on these distributions.

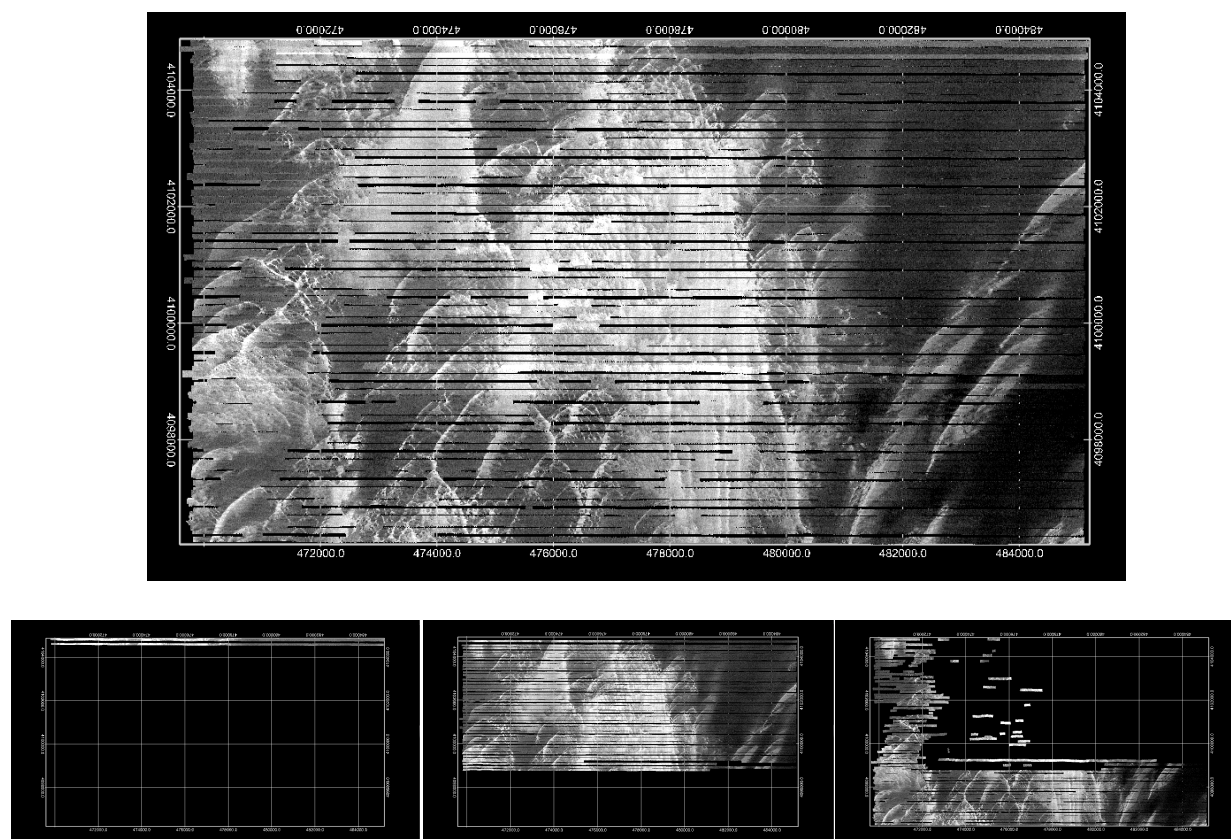


Figure 3: The full sheet of uncorrected backscatter from the port head for sheet H12501 (top) and the sheet broken into the component mosaics labeled H12501_PORT_A (bottom left), H12501_PORT_B (bottom middle), and H12501_PORT_C (bottom right)

Method 1: Full Cross Correlation – Identical Survey Areas

The simplest case is where the two systems have nearly full coverage over the same patch of seafloor at the same time. In this case any temporal variability is eliminated and distributions of returned backscatter are expected to be identical with the exception of a fixed dB offset. The inter-head offset can be easily solved for by cross-correlation of the two distributions. An example where this approach was successfully applied is shown in Figure 4. This small area (approximately four km²) off the Virginia coast was surveyed over a period of six hours. The line spacing was such that each head achieved nearly full coverage. Figure 4 shows the corrected mosaic produced from the compensated heads. Figure 5 shows the distribution on mosaic intensities from both heads and the dB offset taken from the peak of the cross-correlation between the two distributions. The offset between the two heads is taken as the peak value of the cross-correlation, in this case 1.2 dB. Differencing the center of mass of these distributions yields 1.4 dB. If the surveyed area were exactly the same, we would expect these two values to be the same. In fact, any of the additional methods proposed below should work as well in this case. A cross-correlation is simple to implement, robust to outliers, and requires no operator interpretation.

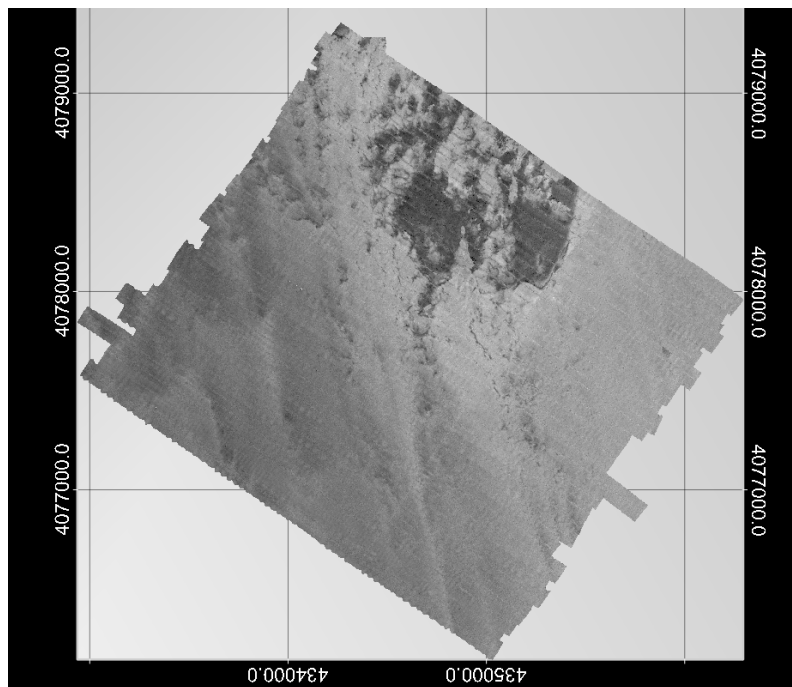


Figure 4: Corrected mosaic from small area 25 nm off coast.

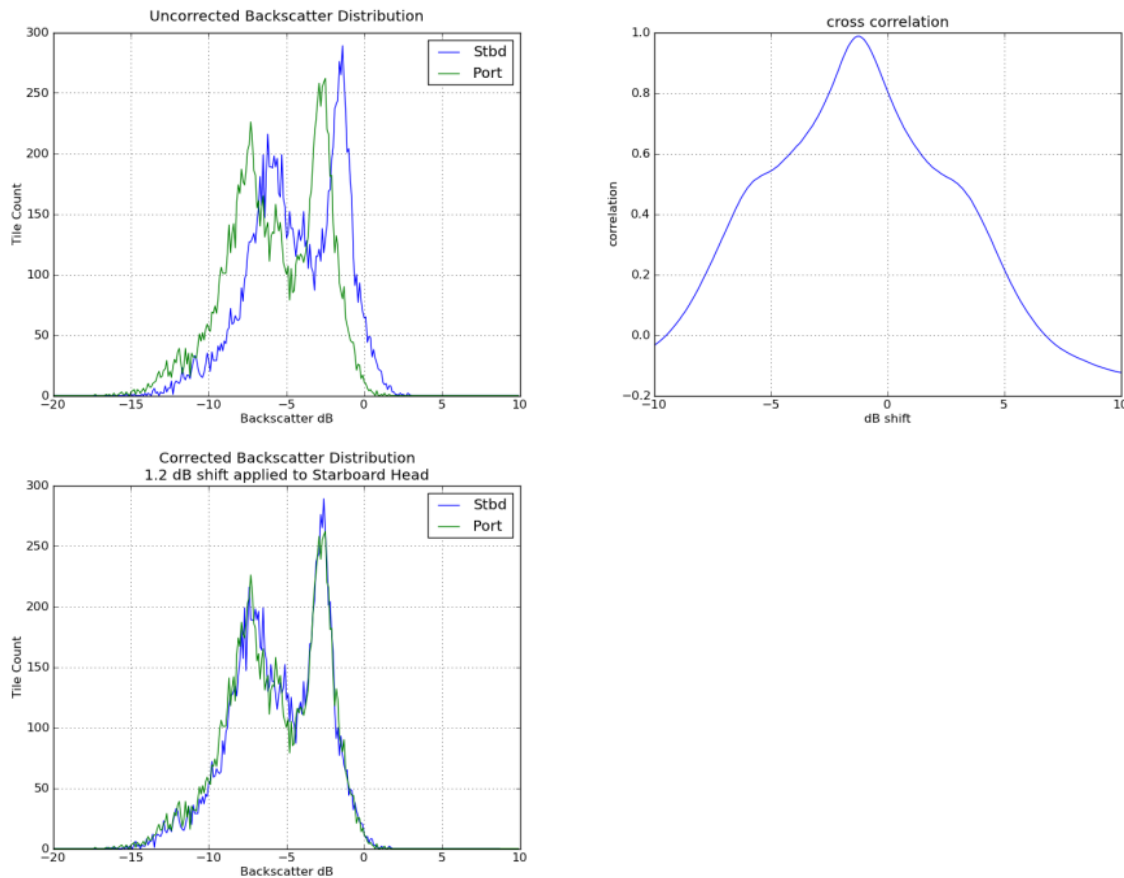


Figure 5: Distribution of mosaic backscatter shown uncorrected (upper left) and corrected (lower), the maximum of the cross correlation between the two distributions (upper right) was used to calculate the offset.

A critical assumption in this method and all subsequent methods is that both systems have linear responses across the operating dynamic range of the system. We (Greenaway and Weber 2010) have previously shown that this is a fundamental assumption of many backscatter processing approaches and have developed a field test to verify that the systems are operated in a regime where this constraint is true.

Disparate Areas

When the surveyed areas of the two systems being compared are not exactly the same, the distributions of backscatter within those areas can no longer be expected to be identical; a simple cross-correlation approach is no longer valid. This may occur when attempting to normalize between different days of a single system or between two systems operating either in tandem (as on the *Hassler*) or two vessels engaged in a joint survey of a larger area. However, so long as the same distinct bottom types are found in both areas it seems possible to tie the two areas together. The following methods are all based on this premise: so long as disparate survey areas can be reasonably assumed to have at least one common bottom type, we should be able to estimate the appropriate normalization offset between the two systems.

Method 2: Visual Gray Scale Matching

This is essentially the method used by Intelmann et al. (2006). In this approach the mosaic image is adjusted to minimize visual discontinuities. This method is programmatically simple and leverages the impressive capability of the human mind to recognize patterns. We include the visual gray scale matching approach here not because we propose any advances to this method, but as a comparison and validation with the other methods that follow. In this case, we set the dynamic range of the gray-scale to a fixed value (15 dB in our case) and adjust the bounds of the color map manually to harmonize the entire image of collected mosaics. This method is easily implemented, but is slow, not readily repeatable, somewhat cumbersome, and requires an attentive operator.

Method 3: Simple Peak Detection

This method is motivated by an observation that many of the mosaics in our survey area have one or more distinct peaks in the distribution of mosaic tile values. A simple peak detector was constructed by removing gaps in the histogram, smoothing with a Hanning window of length 1.5 dB, and finding the positive peaks (locations with a zero slope and negative second derivative). An example is shown in Figure 6.

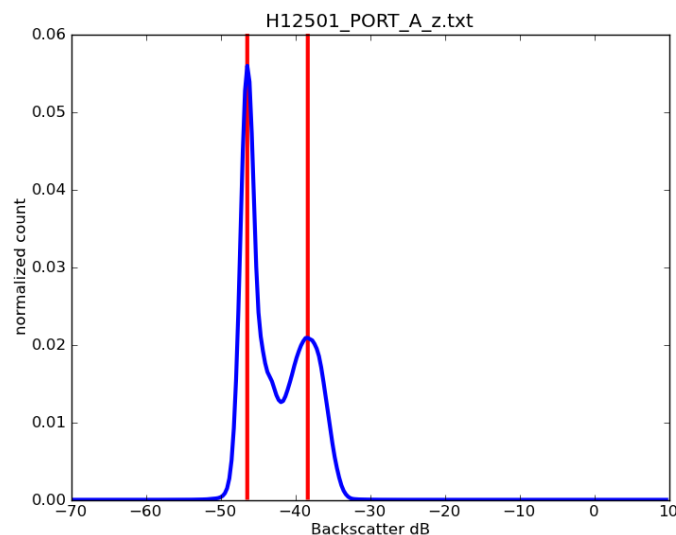


Figure 6: Smoothed distribution of mosaic intensities. Red lines show detected peaks.

For comparisons between areas with only one peak (i.e. one dominant bottom type) the extraction of the offset is trivial; simple differencing of the peak location yields the offset. This approach is not as simple when multiple peaks or different number of peaks is present in the distribution. Figure 7 shows such an example. It is not clear in either of these two examples which peak should be compared to the peaks shown in Figure 6. In our case, this was done by either referencing the mosaic from which the distributions were derived to assign peaks to components (e.g. the lower peak in H12501_Port_A shown in Figure 6 corresponds to the same

material that also makes up the lower peak in H12501_Port_B shown in Figure 7) or by looking at the internal differences between the peaks within a distribution (e.g. the two peaks shown in H12501_Port_A differ by 8 dB, the uppermost and lowest peaks in H12501_Port_B differ by 9 dB, so these two are likely the same material with the middle component of H12501_Port_B representing a material that does not present as a peak in H12501_Port_A). As these two examples suggest, this analysis is time consuming, iterative, and requires an attentive operator. In this sense, this is not a great improvement over the visual gray-scale matching approach.

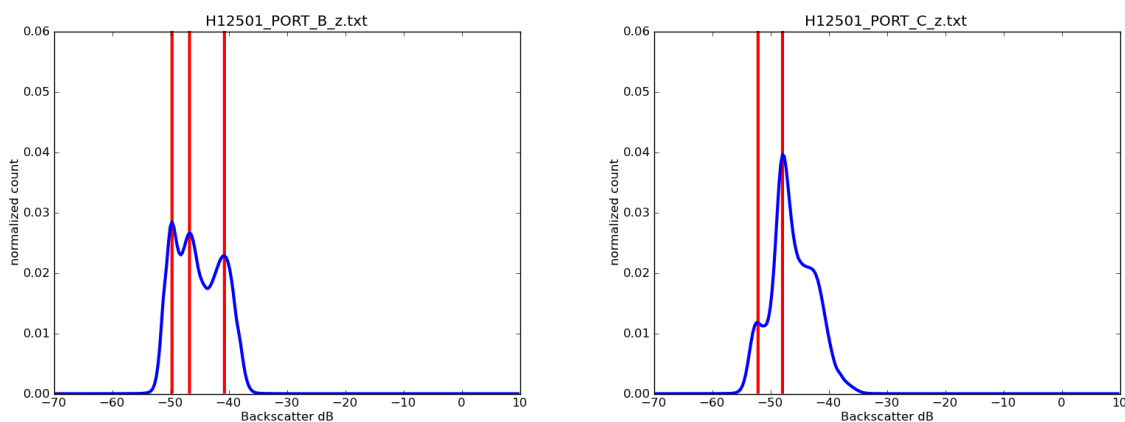


Figure 7: Distributions of mosaic intensities from two areas with the same instrument. Three distinct peaks are apparent in the distribution from H12501_Port_B (left) on the left, but only two in the distribution from H12501_Port_C (right)

Method 4: Mixture Models and Cross Correlation of Components

Both the simple peak detection and the Gaussian peak detection methods discussed in the previous section have serious shortcomings. In the presence of more than one constituent component, interpretation of the results from a peak detection approach becomes complex. In addition, the presence of additional components may skew the distributions and substantially shift the location of the peaks depending on the other constituents. To build on the ideas in both the simple peak detection approach and the Gaussian peak detection result, we introduce a mixture model to estimate the constituent components of the distributions. We then use these constituents to estimate the offset.

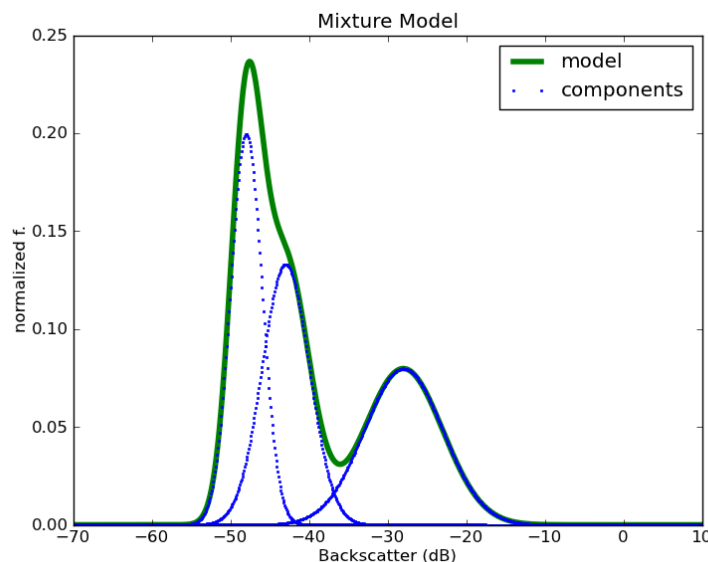


Figure 8: A generic mixture model with three Gaussian components. Components are shown by blue dotted line, mixture by solid green line.

Mixture models are used to estimate the parameters of constituent populations that sum to the whole distribution. Simons and Snellen (2009) have shown that a mixture of Gaussian components can represent the distribution of backscatter from a complex seafloor. We justify the application of the central limit theorem in our case by recognizing that each mosaic tile has a large number of contributing samples. Each tile typically has an average of about 15 contributing pings with up to 25 samples per ping

The work described here was completed using a univariate mixture of normal distributions in an Expectation Maximization algorithm from the Python module Pymix (<http://www.pymix.org/pymix/>). This algorithm requires a seed estimate of the number of components and their parameters. For a given set of regions to be modeled, the previously described simple peak detection algorithm was performed. The distribution with the most number of peaks was used to seed the mean value of each component. For distributions with fewer peaks, the same peak locations were used, but were offset by the difference in the mean value of the distribution. The model was then allowed to run for a maximum of two hundred increments, or until the difference in log-likelihood of following iterations was less than an admittedly arbitrary value of 0.3. The result is an estimate of the constituent distributions. The results of the mixture model against the three distributions previously introduced are shown in Figure 9.

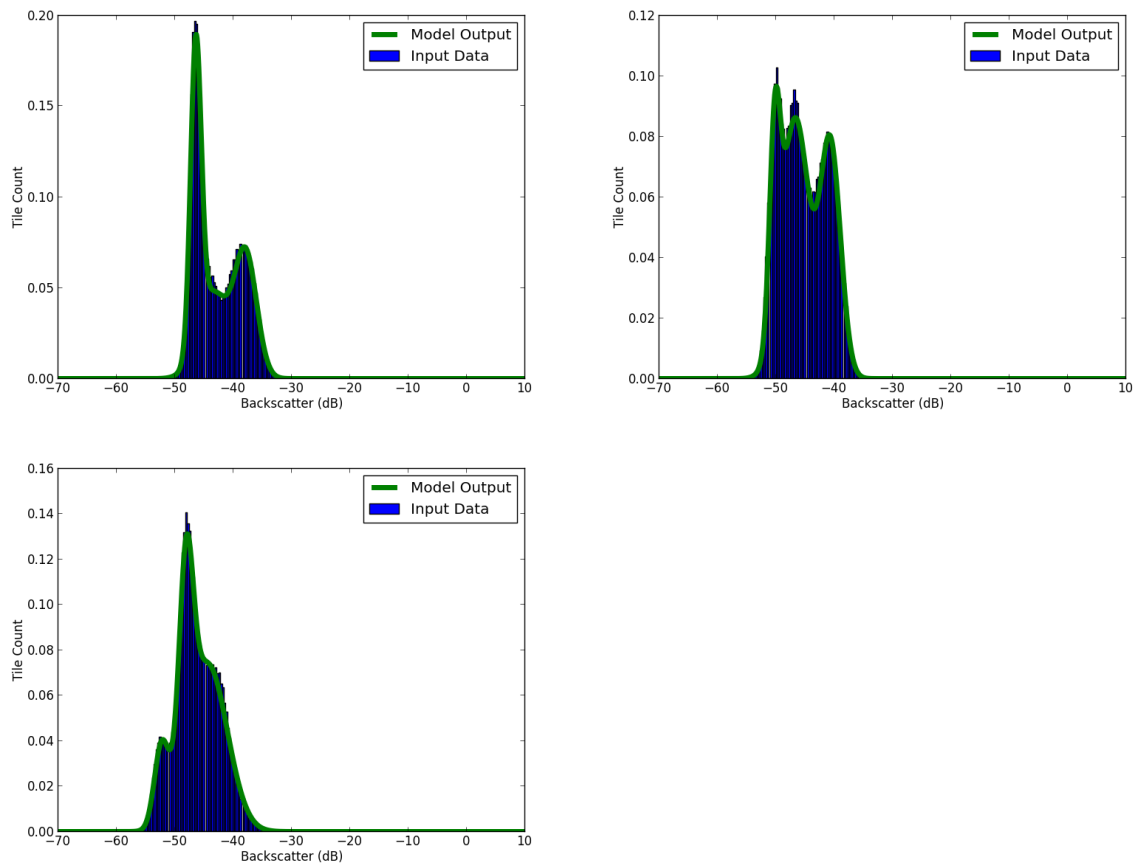


Figure 9: Three component mixture model (green line) and measured distribution (blue columns) for H12501_PORT_A (upper left), PORT_B (upper right), and PORT_C (bottom)

Because we are only looking for the offset between two distributions of normalized backscatter collected from different echosounders, we do not really care about the fractional components of the mixture. We are assuming is that each distribution is comprised of different fractions of at least some of the same components. As a first step, we assign all the components of the model an equal weight, thus preserving the information about what is in each mixture, but intentionally discarding the information on the relative proportion of each component. In essence, we create an artificial distribution, a distribution that would have resulted if there were equal amounts of each component. The results of this process are shown in Figure 10.

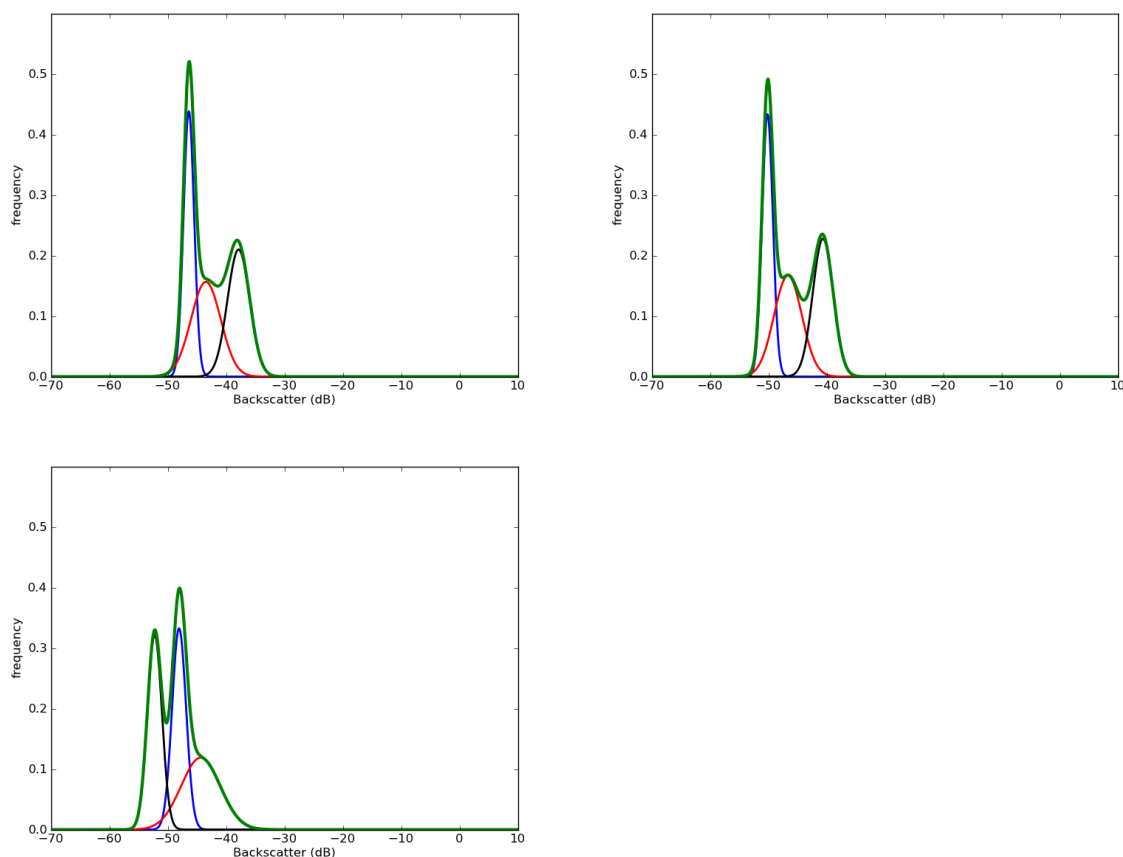


Figure 10: Three component mixture model (green line) with equal component weights. Components are shown in black, blue and red lines. H12501_PORT_A (upper left), PORT_B (upper right), and PORT_C (bottom)

After discarding the information on component weight, we then cross-correlate that artificial distribution with similarly derived distribution from the one area selected as the reference. The maximum of the cross-correlation function is taken as the normalization offset between the two areas. This approach solves the major deficiencies of the simple peak detection or the single Gaussian peak detection approaches. It utilizes the information in the entire distribution and accommodates varying constituents.

While this approach deals with varying fractions of constituents well, model results show it can be skewed by introduction of additional components in one of the distributions that is not in the other if the additional component has a highly overlapping distribution with one of the other components. An example is shown in Figure 11. This can bias the cross-correlation and thus the derived offset. To address this, we cross-correlate the individual components (again normalized to discard fractional constituent information) one by one. While the cross-correlation of any Gaussian with any other will result in a peak in the cross-correlation, the correlation coefficient will be smaller if the distributions are dissimilar. In this fashion, if one distribution has three constituents and the other two, we perform six cross-correlations. The components that are shared between the two distributions should yield the same offset value and also high correlation coefficients. We extract the location and value of the maximum of the

cross correlation and then, allowing for some variability through a moving average, we bin and sum the results. The offsets that are supported by strong correlations and multiple components that correlate with the same offsets will sum together. This process is shown for a synthetic mixture in Figure 11. In this case, the full cross-correlation of the models yields an offset estimate with an error of 1.1 dB, while the component-by-component approach yields the correct offset to within the model tolerance (0.1 dB). While this approach has advantages in model runs, it proved to be unstable with real data and did not provide as consistent as the simple cross-correlation of the equalized distributions.

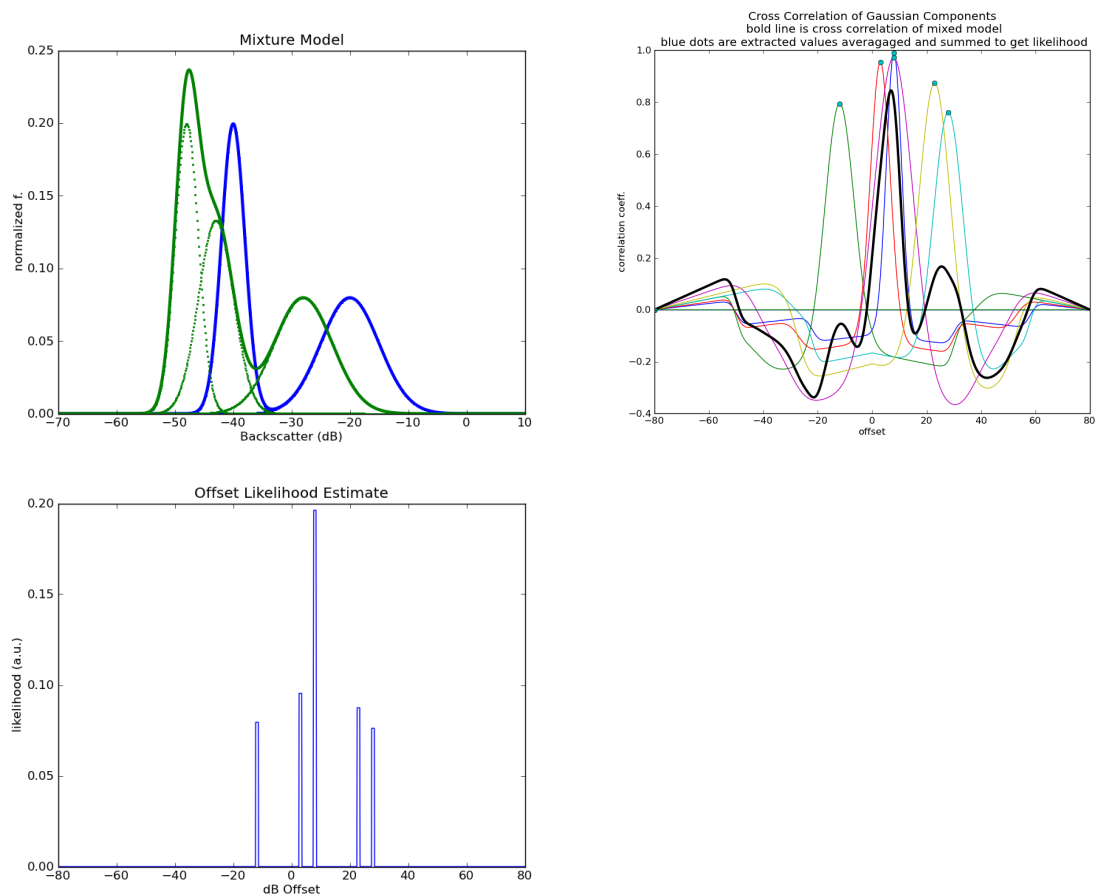


Figure 11: Results with a two constituent model (blue) and three constituent model (green). The Gaussian components are shown by dotted line, the resultant mixture by a solid line (upper left). The cross-correlation of the mixture (black line) and the individual components (colored lines) is shown in upper right panel, extracted peaks indicated with dot. The summed offsets are shown in lower panel.

Unlike the methods discussed in earlier sections, multiple components of the comparison seafloor improve the performance of the mixture model approaches.

Results

Offsets derived from this method compared with visually estimated offsets are shown in Table 1. All offsets have been calculated relative to H12505_Port_A. The sonar hardware used for H12424 (both port and starboard) was different than was used for the other areas. The large offsets for the port head for H12424 is due to errors in the initial implementation of the FM

system for this head. An example of an uncorrected and corrected mosaic is shown in Figure 12.

Area	Visual	Mixture Model	Difference	Note
H12501_PORT_A	0.0	0.0	0.0	
H12501_PORT_B	-3.0	-3.7	0.7	
H12501_PORT_C	-4.0	-6.0	2.0	
H12501_STBD_A	7.0	8.2	-1.2	Very small area
H12501_STBD_B	4.0	4.3	-0.3	
H12501_STBD_C	3.0	2.4	0.6	
H12504_PORT_A	0.7	3.0	-2.3	Small area, different bottom type?
H12504_PORT_B	5.0	5.9	-0.9	
H12504_STBD_A	4.0	5.6	-1.6	
H12504_STBD_B	11.0	4.9	6.1	Very small area
H12505_PORT_A	0.0	0.0	0.0	
H12505_PORT_B	4.0	5.0	-1.0	
H12505_STBD_A	2.3	3.1	-0.9	
H12505_STBD_B	9.0	9.7	-0.7	
H12424_PORT_A	14.0	16.2	-2.2	FM match filter poorly implemented
H12424_PORT_B	18.0	18.9	-0.9	FM match filter poorly implemented
H12424_PORT_C	-20.0	-17.2	-2.8	FM match filter poorly implemented
H12424_PORT_D	-6.0	-3.0	-3.0	
H12424_STBD_A	2.0	4.0	-2.0	
H12424_STBD_B	1.0	2.9	-1.9	Very small area

Table 1: Offsets derived from visual estimation and from the mixture model method. All values are in dB and are relative to H12505_Port_A.

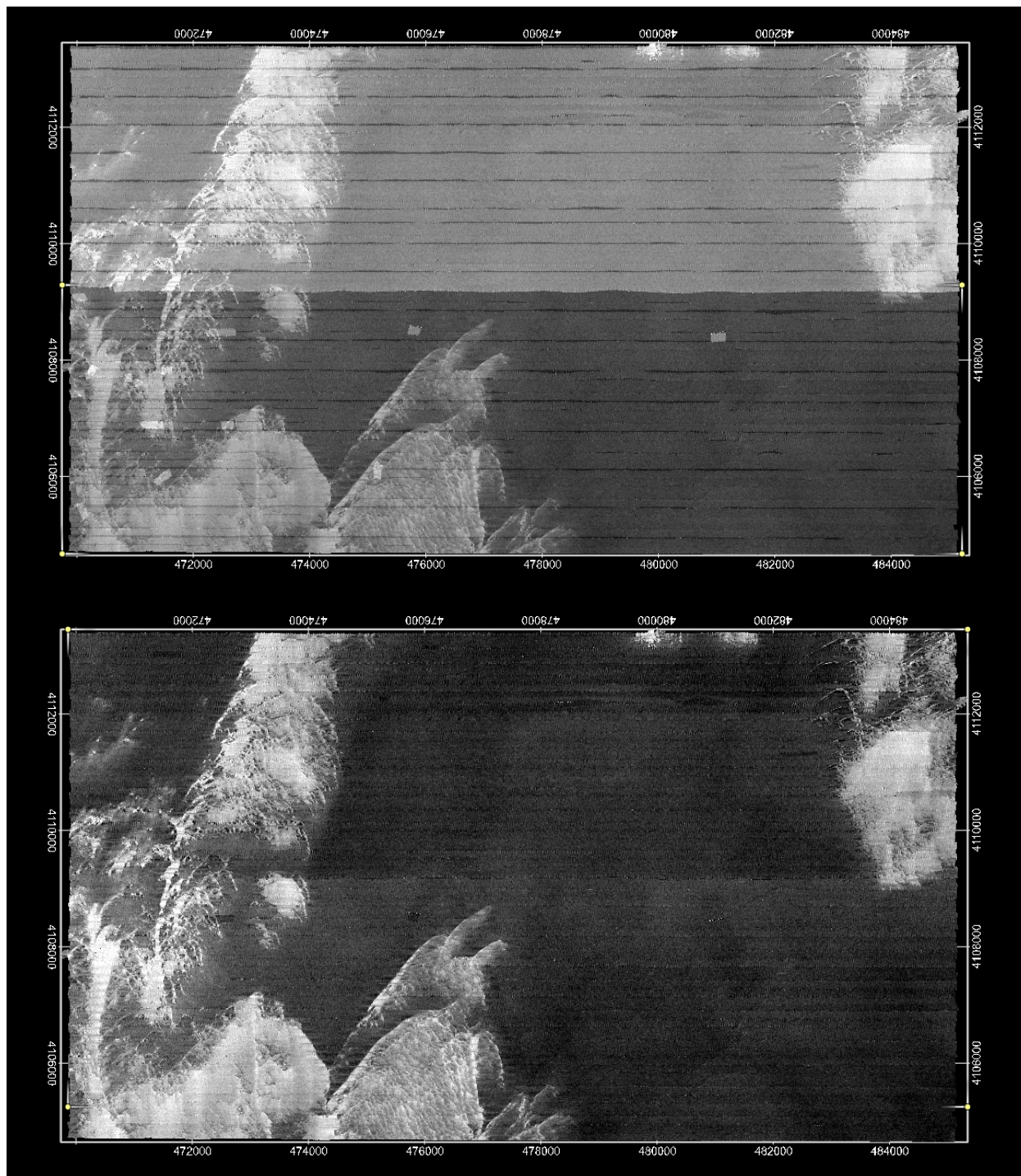


Figure 12: Uncorrected (top) and corrected (bottom) mosaic. Corrections are based on mixture model derived offsets. The upper image has 25 dB of dynamic range in the gray scale. The dynamic range has been lowered to 15 dB in the lower image.

Conclusion

We develop a method to normalize between independent systems by initially segmenting the data into consistent parts and then look at the distribution of mosaic intensities. Where we can

ensure that the surveyed area is identical or nearly identical between compared systems, we show that a simple cross-correlation of the mosaic distribution provides a robust estimate of the offset between the systems. This approach will likely be useful in developing backscatter patch tests that solve for this offset much like the multibeam patch test solves for unknown angular biases. In more complex comparisons, we develop a general approach using mixture models and cross-correlation of the components. This method is an improvement over the simple peak detection methods. Significantly, this method is free of the requirement of operator interpretation. The techniques outlined in this paper should be of interest to those interested in integrating multiple sensors into a coherent backscatter survey effort.

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