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# Clustering Acoustic Backscatter in the Angular Response Space

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## ABSTRACT

Backscatter mosaicking is a necessary step in the analysis and interpretation of sidescan and multibeam sonar records. However, due to limitations intrinsic to the mosaicking technique, backscatter mosaics are restricted in their capacity to unambiguously discriminate seafloor properties. A more adequate technique to characterize the seafloor is the analysis of backscatter angular responses, since those responses are intrinsic properties of the seafloor. This technique sometimes lacks spatial resolution, however, as the analysis is limited to the swath width of the sonar. In this paper, we propose an approach to combine mosaicking and angular response analysis techniques in an attempt to take advantage of both the spatial resolution of the mosaic, and the angular resolution derived from the angular response analysis.

In order to test these ideas, we used acoustic backscatter acquired by a Reson 8101 (240kHz) multibeam sonar during normal survey operations conducted on the NOAA Ship FAIRWEATHER around Cape Decision, Alaska in spring 2005. First, we defined parameters that uniquely described the angular responses, and treated those parameters as a feature vector in a multidimensional space. The parameters were then clustered with a simple unsupervised clustering algorithm. The result of the clustering analysis defined areas on the seafloor which had similar angular responses, which we called themes. We then used these themes to develop more robust indicators of angular response from their coverage areas, which were finally used as Angle Varying Gain correction tables to assemble an enhanced mosaic.

# INTRODUCTION

The preparation of acoustic backscatter mosaics is a necessary step in the analysis and interpretation of sidescan and multibeam sonar records. Mosaics are normally presented in the form of image maps that hopefully represent the spatial distribution of the backscattering strength in the surveyed area. These maps have practical applications in a broad range of disciplines including marine geologic, geotechnical, hydrographic, biological, fisheries and environmental research, as they portray, in high spatial resolution, the distribution of features and the overall morphology of the seafloor.

There are two major obstacles in the preparation of backscatter mosaics. First, multibeam and sidescan sonars do not normally record directly values of backscatter strengths, but rather they collect data samples of relative magnitude that often do not come with any further documentation. Second, even when it is possible to reduce the sonar observations to backscatter strengths, we are still left with the task of removing the backscatter angular response, which represents the way that the backscatter strength changes with the angle of incidence. The removal of the backscatter angular response is an essential step in order to produce mosaics that show consistency across the swath (for a homogeneous seafloor), and not an angular variation. Removal of angular variation is not an easy task, as the angular response is an intrinsic characteristic of the seafloor. Therefore, we need to know something about the seafloor prior to assembling a backscatter mosaic. This is not a practical requirement, as the primary idea behind assembling acoustic mosaics is to obtain some insight about the nature of the seafloor.

Surprisingly, the same angular response that poses a major problem to the assembly of backscatter mosaics is a critical piece of information in many methods for remote seafloor characterization. Many studies have shown the potential of using angular response for the remote estimation of seafloor properties (de Moustier and Matsumoto, 1993; Pouliquen and Lyons, 2002; Fonseca and Mayer, 2007). Examples of important seafloor acoustical and physical properties that can be estimated based on the angular response analysis are the grain size, acoustic impedance (product of density and sound speed), acoustic attenuation and the acoustic roughness of the near-surface sediments. As with the mosaicking problem, there are two major obstacles to the analysis of angular responses. First is the requirement of having accurate measurements of backscatter strength. Second is the implicit assumption that the seafloor is uniform across the swath, which is often not the case.

## SPATIAL RESOLUTION VERSUS ANGULAR RESOLUTION

If we stipulate the importance of the angular response, it becomes obvious that any mosaicking procedure that requires the removal of the angular response information to produce coherent mosaics reduces our ability to derive quantitative seafloor characterization information. The conclusion is that mosaicking implies a loss in angular resolution. On the other hand, the analysis of angular responses preserves the full angular resolution of the sonar signal, and consequently our ability to characterize the seafloor. However, this analysis is limited to the swath width of the sonar, which reduces substantially the spatial resolution. So we can say that mosaics have high spatial resolution, but low angular resolution, while the angular response analysis has low spatial resolution but high angular resolution. These two methods appear to be complementary.

A preliminary approach to combining these two methods would be to take advantage of the high spatial resolution of the mosaic, and use image processing techniques, like texture analysis, to segment areas with similar backscatter signatures. With that, we could then calculate an average angular response for the segmented area, and this average angular response could then be used for seafloor characterization as well as the assembly of a more accurate mosaic. The major flaw in this idea resides in the fact that the mosaic is assembled based on some *a priori* assumptions related to the angular response. As a result, it becomes very difficult to justify this sort of circular reasoning, which suggests the use of mosaics that were assembled based on angular responses, to segment areas with similar textures, and then the use of the angular response of those segmented areas to assemble a new mosaic, and so on.

A more promising solution is the use of clustering analysis techniques to separate areas of similar angular response on the seafloor, instead of segmenting areas of similar texture on the mosaic. This choice is justified by the fact that the angular response is the raw observation of the sonar, and exists prior to the mosaicking. In order to accomplish such clustering, we first need to characterize the angular response by extracting parameters that uniquely describe it. Those parameters can be treated as a feature vector in a multidimensional space: the angular response space. The feature vectors can then be clustered with simple unsupervised clustering algorithms. The result of the clustering analysis will define areas on the seafloor with similar angular responses, which we call themes. Each theme will have a unique average angular response, which can then be used for a more robust seafloor characterization. The average angular response can also be used as an Angle Varying Gain table necessary for the assembly of improved mosaics.

## FROM RAW DATA TO BACKSCATTER STRENGTH

In order to test the approach described above, we used acoustic backscatter acquired by a Reson 8101 (240kHz) multibeam sonar during normal survey operations conducted on the NOAA Ship FAIRWEATHER around Cape Decision, Alaska in spring 2005. The digital numbers registered in the Reson 8101 sonar record are not exactly values of backscatter strength, so it was necessary to radiometrically correct them, and to geometrically correct and position each acoustic sample in a projected coordinate system (Fonseca and Calder, 2005). First, all the gains and time-varying gains applied during acquisition were removed from the original observations using information provided by the manufacturer. Then, the observations were corrected for the terms of the sonar equation, which are: transmittion loss, attenuation in the water column, area of insonification, source level, and transmit and receive beam patterns. Additionally the backscatter values were corrected for the seafloor bathymetric slope. The result of this processing was the corrected backscatter angular response for the survey area.

## FROM ANGULAR RESPONSES TO MOSAICS

The corrected backscatter angular responses cannot be directly mosaicked since the resulting mosaic would not be uniform across the swath, i.e., it will show high values near nadir, and lower values at greater incident angles. As an exercise, such a mosaic was assembled and the results are shown in Figure 1. It is clear that the resulting artifacts make the interpretation of the mosaic extremely difficult. The standard technique used to avoid these artifacts is the Angle Varying Gain (AVG) correction; the difficulty is in choosing which AVG curve to use.

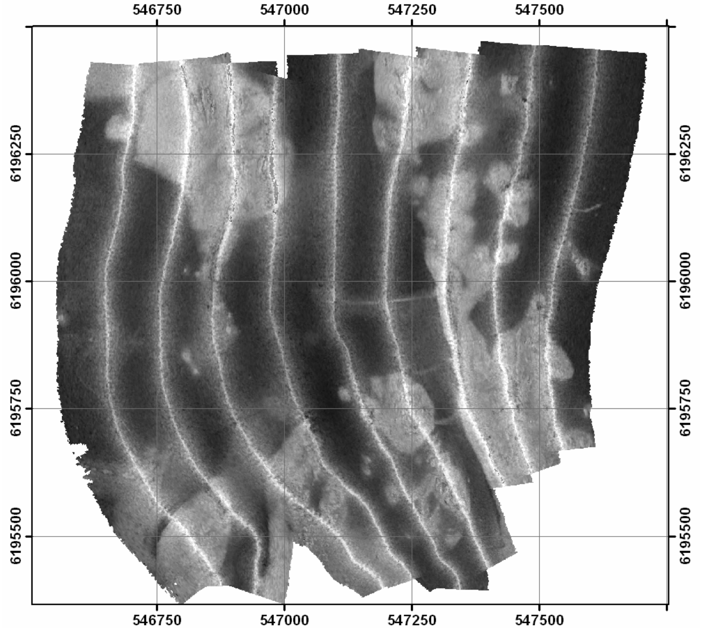


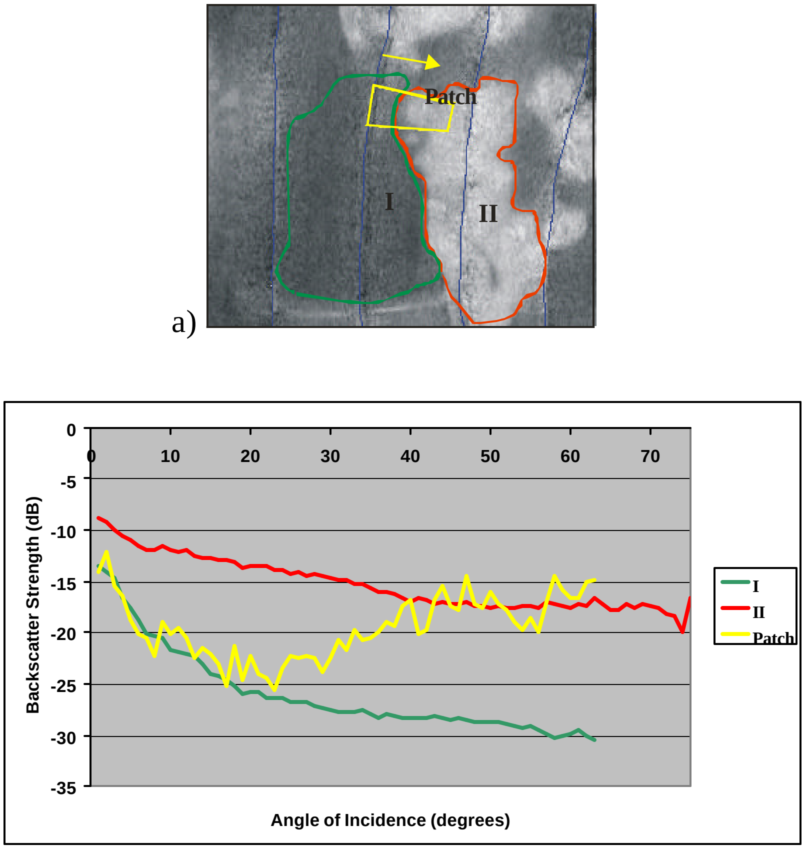
Figure 1 –Acoustic backscatter mosaic of the surveyed area assembled with no AVG correction. The data was acquired with a Reson 8101 (240kHz) around Cape Decision, Alaska.

There are many standard methods used to calculate the AVG corrections necessary to normalize the backscatter strength across the swath (e.g. remove the backscatter angular response). The most common ones are the Lambertian corrections with two parameters (Hammerstad et al., 1991), Chebyshev filters (Cervenka and deMoustier, 1993) and moving averages (Chaves Jr, 1986; Fonseca and Calder 2005). All of these methods are empirical and equally valid from the perspective of data analysis and digital image enhancement and therefore the choice is subjective. Our goal here is to derive a better AVG curve based on clustered AVG data directly derived form the sonar returns.

## EXTRACTING PARAMETERS FROM THE ANGULAR RESPONSE CURVE

The discussed methods for AVG correction are limited in their capacity to remove the backscatter angular responses as they assume that the seafloor is uniform across the swath and along the navigation track within the length of the moving average. The same argument is valid for methods of acoustic seafloor characterization based on the analysis of the angular response, which also assume uniformity across the swath and for a certain number of pings in the along-track direction.

A more robust way of analyzing angular responses, or of properly removing them while assembling mosaics, is to separate areas with similar angular response on the seafloor - the themes - and calculate one AVG table per theme, rather than across the sonar swath. So the angular response would not be limited to the swath width of one acquisition line, but would rather relate to all beams from all acquisition lines that intersect a certain theme on the seafloor. Figure 2 shows one area where the angular response is not uniform across the swath, as it lies at the intersection between two different seafloor types. The angular response of this area is clearly the combination of the angular response of the surrounding areas.



a)

b)

Figure 2 – a) Detail of the backscatter mosaic showing one seafloor patch, depicted as the yellow box, which crosses two distinct seafloor themes, (I) and (II). The yellow arrow shows the look direction of the sonar in the patch b) Average angular responses of the themes and the patch. The angular response of the patch, the yellow curve, appears to be the combination of the curves I and II.

In order to separate areas with similar angular responses, we first need a way to characterize and quantify the angular response curves. In this work we will use the methodology called Angular Range Analysis (Fonseca and Mayer, 2007) which suggests a list of parameters (ARA features) to be extracted from the angular response curve. In that analysis, the parameters are extracted from seafloor patches, which are defined as the stack (average per angular bin) of a number of consecutive sonar pings (normally between 20 and 30), chosen to approximate the dimension of the swath width in the along-track direction. Each stacked angular response defines two distinct seafloor patches, one for the port side and another for the starboard side. The stacked angular responses are then dived in angular ranges: the near range includes incident angles from 0° to 25°, the far range from 25° to 55°, and the outer range from 55° to 85° (Figure 3). In the near range, four parameters are extracted from the seafloor patch: the near-mean backscatter, the near-slope, the near-intercept (at 10°) and the near-angle, which is the average grazing angle for all the sounding stacked in this range. In the far range, the parameters far-mean, far-angle, far-slope and the far-intercept at 40° are calculated, and in the outer range, only the outer-mean is extracted. The last parameter is the orthogonal distance, which is extracted from an intercept-slope graph (Fonseca and Mayer 2007).

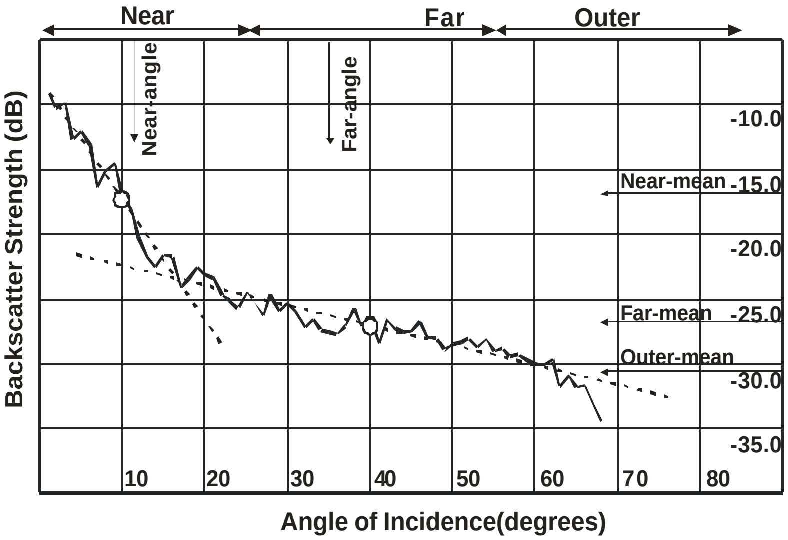


Figure 3 – ARA-Parameters extracted from the angular response curve.

CLUSTERING IN THE ANGULAR RESPONSE SPACE

We can treat the ARA parameters a feature vectors for the patches of the survey area, and then calculate the z-score for each parameter. The Z-score of a variable is defined as the variable minus its mean divided by its standard deviation, and is a common statistical technique to normalize diverse parameters to a common dynamic range. Once the z-scores are calculated, we then apply an unsupervised k-means clustering algorithm (Hastie et al, 2001) to generated 9 clusters of similar angular responses. The result of the clustering algorithm is shown in Figure 4, where the z-score statistical means of the ARA features are plotted for each cluster. In Figures 5a, the center of each seafloor patch is overlain on top of the mosaic, and is color-coded based on the cluster number. These patch centers are then used to generate Thiessen polygons (Burrough and McDonnell, 1998), that, when amalgamated, define the boundaries of the seafloor themes (Figure 5b). Note the low spatial resolution of the Thiessen polygon, as they are limited to the angular response resolution.

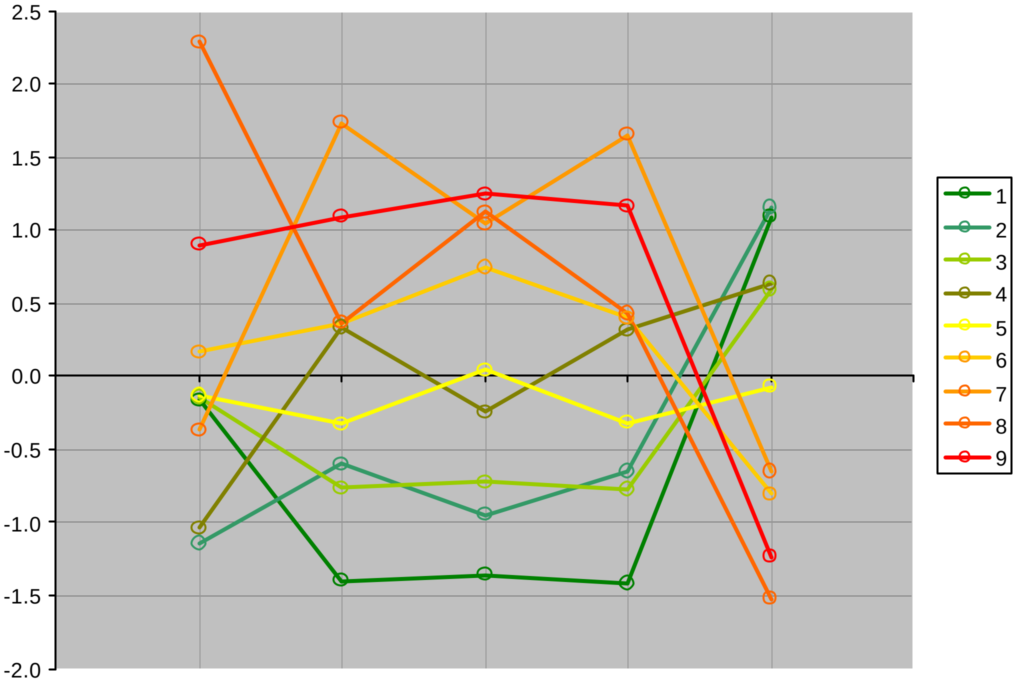
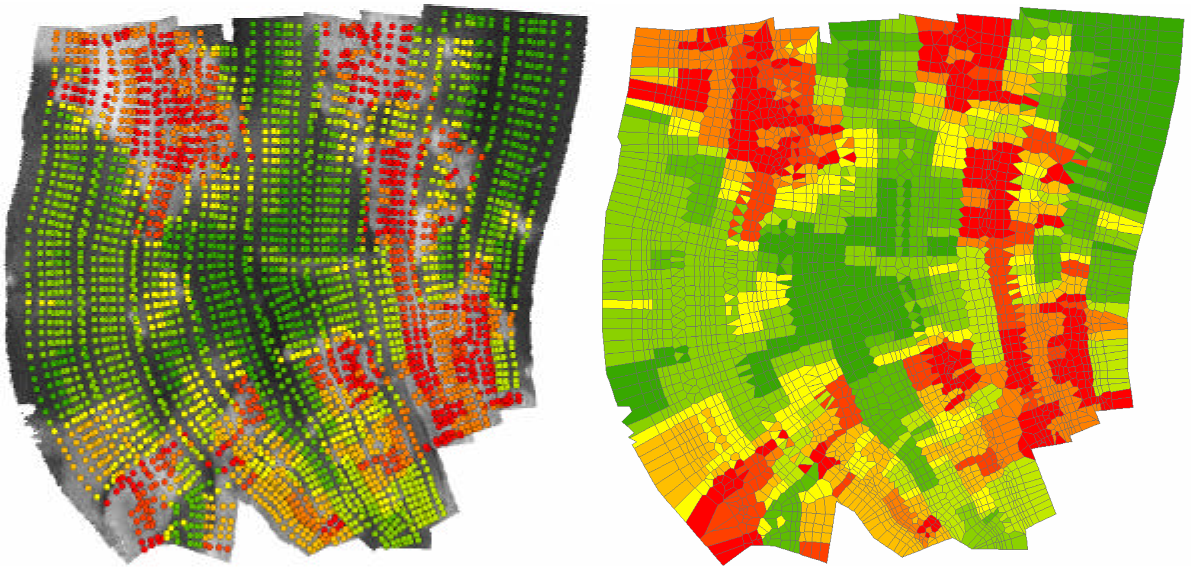


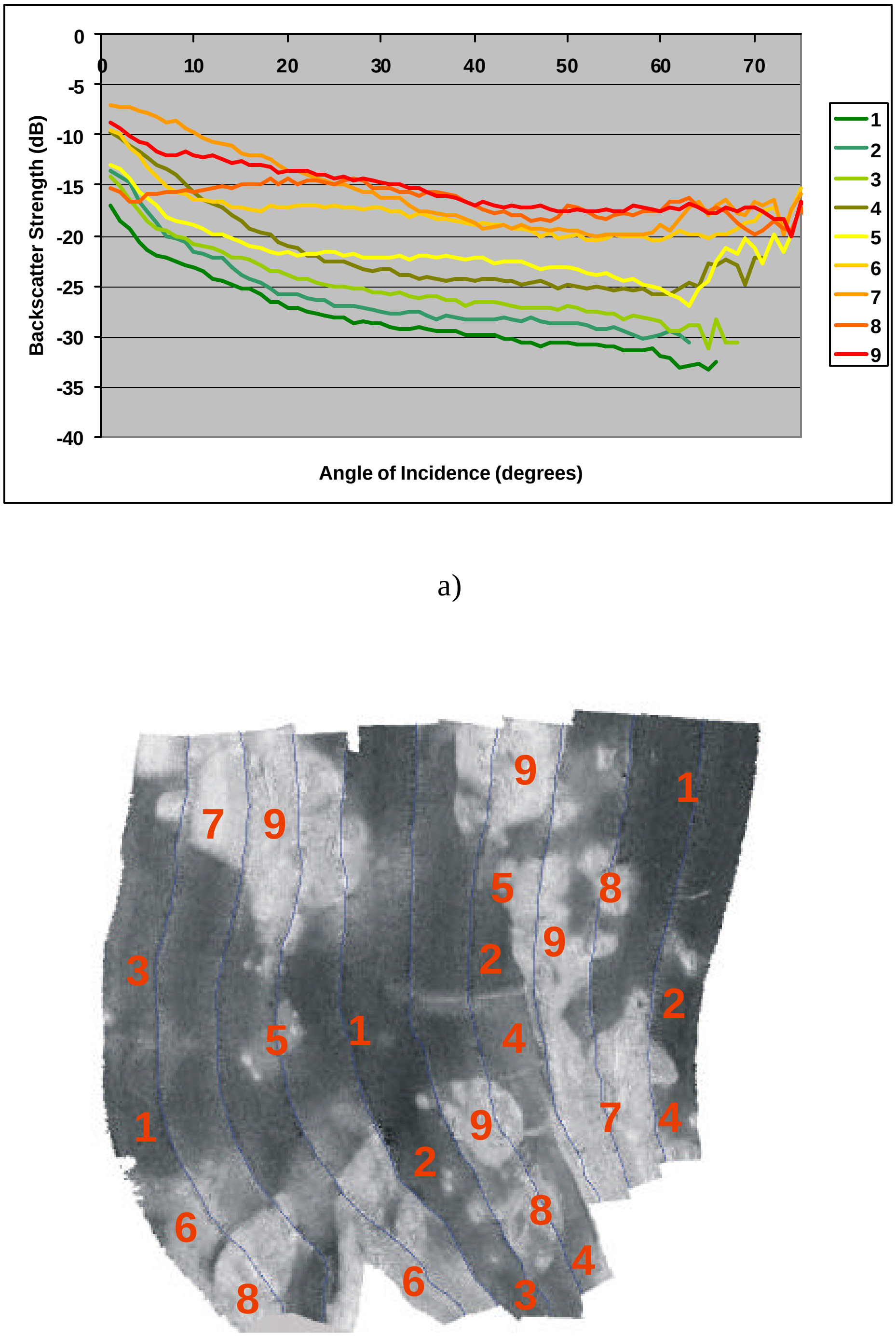
Figure 4 – Z-score means of the ARA features for the 9 clusters.

The average angular responses of the themes are then regarded as AVG tables, and used to assemble the mosaic shown on Figure 6b. (The numbers displayed in this figure are the cluster numbers). This enhanced mosaic has fewer along and across track artifacts The simultaneous analysis of the mosaic and the cluster numbers shows the spatial relationships among areas with similar angular response, with the boundaries of those areas defined by the mosaic. Figure 6a shows the average angular responses for the 9 themes. Note that the theme 5 clustered angular response similar to the yellow curve shown in Figure 2, which suggests that this cluster has separated areas that have non uniform angular response across the swath. Our criticism of k-means clustering is that the number of clusters must be specified *a priori*. The choice of too many or too few clusters may lead to mixed result such as the one shown in theme 5, with consequent interpretations that are physically difficult to justify. We consider k-means clustering a methodologically simple preliminary analysis used to bootstrap this effort, and we are actively seeking better methods for the future.



a) b)

Figure 5 – a) Backscatter mosaic with the center of the patches color-coded with the cluster number. b) Thiessen Polygons calculated based on those centers.



a)

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Figure 6 a) Average angular response for the 9 themes. b) Final mosaic with AVG correction based on seafloor themes. The red labels are the theme numbers, and the blue lines are the navigation tracks.

## CONCLUSIONS

Any mosaicking technique, which requires the removal of the angular response information among other assumptions, reduces our ability to apply quantitative seafloor characterization techniques. The analysis of angular responses improves our ability to characterize the seafloor, but its spatial resolution is limited to the swath width of the sonar. The proposed approach which combines mosaicking and angular response analysis improves the spatial resolution of the angular response analysis and produces mosaics with fewer along-track and across-track artifacts. Future work will include a search for better methods for clustering the angular responses in the angular response space and the development of methods to merge the mosaic and the results of the clustering analysis.

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