Non-Rayleigh Echoes From Resolved Individuals and Patches of Resonant Fish at 2–4 kHz

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Non-Rayleigh Echoes From Resolved Individuals and Patches of Resonant Fish at 2–4 kHz

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***Abstract*—In this paper, the statistics of the echo envelope measured from fish is studied over a range of scattering geometries in the frequency band 2-4 kHz. In this frequency band, not only are these particular swimbladder-bearing fish resonant (at about 3.7 kHz) resulting in strong echoes, but also their target strength is narrowly distributed at these frequencies. In addition, their size distribution is narrow. Thus, it can be assumed that the echo variability as measured through the receiver of the sonar system is principally due to beampattern effects of the sonar, spatial variability of the fish, and interference between overlapping echoes. The measurements were conducted over Georges Bank near Cape Cod, MA, using a broadband downward-looking echosounder in a short-range, direct-path geometry. Echoes from sequential pings were grouped according to whether they 1) involved resolved echoes from individual fish, 2) were entirely within a single patch of fish, 3) spanned the edge of a single patch of fish, or 4) spanned multiple patches of fish. The resultant distributions of echoes were compared with theoretical probability density functions (pdfs). The echoes are determined to be strongly non-Rayleigh, with beampattern effects a major factor, for all geometries except for the case when all echoes are from within a single patch. Recommendations are made for the appropriate echo pdf for these scattering geometries.**

***Index Terms*—Echo statistics, fish, reverberation.**

I. Introduction

THE statistics of echoes from fish are important to understand whether the active sonars are short range in which there is a direct path between the sonar and fish or long range which involves the ocean waveguide and includes effects due to interactions of the echo with the seafloor, sea surface, and heterogeneities of the water column. For example, with short-range downward-looking systems which are routinely used to assess fish stocks, a motivation has been to improve the accuracy of acoustic assessment of fish distributions, either through incorporating the echo statistics into echo integration methods or using the statistical information directly [1]–[3]. For long-range, horizontal-looking systems, a motivation has been to improve the performance of active sonar systems when fish are considered to be a source of “noise” in the proximity of a different target of interest [4].

Regardless of the motivation, there have been several key elements in the studies of echo statistics: 1) statistical variability of echoes from individual resolved fish (without sonar beampattern effects) as related to their random orientation relative to the direction of the incident acoustic signal [5]–[8]; 2) statistical variability of echoes from individual fish (measured with a directional sonar) as a result of being randomly located in the sonar beam [9]–[12]; 3) statistical variability of echoes (measured by a directional sonar) due to a directional sonar beam sweeping across an aggregation of fish or multiple aggregations of fish [12]–[19]; and 4) influence of waveguide effects, such as multiple interactions of the fish echo with the seafloor and sea surface, on the statistics of the echoes [20].

In this third case above, the variability is related, in part, to a combination of directionality of the sonar beam, patchiness of fish, and heterogeneity of fish within a given patch. For example, the spatial resolution of the sonar in relation to the size of the patch is important, since the echo statistics (and the degree to which they are non-Rayleigh) depends strongly upon how many patches are in the resolution cell [1], [12], [16], [21]. The patchiness has been shown to be variable over a wide range of scales, from meters to kilometers, as demonstrated in the review of data from short-range direct-path sonars in [22], and the various works involving long-range sonars, such as in [4] and [23]–[29]. In the work of [4] involving a broadband mid-frequency sonar (1–9 kHz) detecting fish at ranges up to 10 km in a 200-m-deep waveguide, the statistics of the echoes from patches of fish were shown to be non-Rayleigh. Furthermore, echoes were demonstrated in [4] to survive an energy normalizer, a key metric of clutter.

The vast majority of the studies with short-range, direct-path sonars have involved acoustic frequencies in the tens to hundreds of kilohertz. In this frequency region, the variability of echoes from individual resolved fish is a major factor as listed in 1) above. In this case, the echo from individual resolved fish as measured with a directional sonar is related to the convolution of the probability density function (pdf) of the echo from the fish without beampattern effects and the pdf associated with being randomly located in the beampattern itself. Although the beampattern itself is not random, once a scatterer is randomly located in the beam, the beampattern weighting factor becomes a random variable. The randomized weighting factor is referred to, compactly, as the “beampattern pdf.”

There has been no experimental study that directly isolates the beampattern effects. Specifically, at the high frequencies, the

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echo from the fish (without beampattern effects) is highly variable (Rayleigh-like). Given the fact that the variable nature of the fish echo (without beampattern effects) is not fully known, beampattern effects could not be completely separated from the high-frequency fish echo data to rigorously study effects due to the beampattern. Furthermore, in the case of aggregations of unresolved fish (short-range or long-range sonars), although there has been reasonable characterization of the general statistical properties of the echoes in previous studies, there has not been a controlled study directly relating parameters of the statistics to the precise scattering geometry. Specifically, the studies have not accounted for the precise manner in which the sonar beam sweeps across a patch—the percentage of the sweep that the beam remains within a patch, whether the beam sweeps across a patch edge, or whether it sweeps across multiple patches.

Recently, a broadband echosounder has been used at short ranges in the down-looking direction to exploit the resonance frequency of swimbladder-bearing fish [30]. Through use of several broadband channels, the system spans, with some gaps, most of the frequency range 1.7–100 kHz, and has been used in recent studies of Atlantic herring. These fish contain swimbladders for buoyancy and have been observed to resonate at about 3.7 kHz when residing near the seafloor in depths of approximately 200 m [30]. In contrast to the higher frequency studies cited above, the scattering by fish at the lower frequencies (single digit kilohertz) is essentially nondirectional, resulting in a narrow distribution of echoes from resolved fish (not including the sonar beampattern). Furthermore, at these lower frequencies, contributions to the scattering such as from zooplankton are negligible [30]. Since the lengths of these fish were observed to be narrowly distributed, the remaining contributing factors to echo variability are beampattern effects, spatial variability, and interference between overlapping echoes. In the case of resolved fish, beampattern effects under these conditions (low frequency, narrow distribution of echoes from fish not including beampattern) can be isolated.

In this paper, statistics of echoes from fish are revisited, but now at lower frequencies (2–4 kHz) where the target strength of each (resonant) fish is narrowly distributed and with data windows that help connect parameters of the theoretical pdfs to the scattering geometry. The echo statistics, as derived from data from the new broadband system, are studied over a range of scattering geometries, beginning with the case of the resolved scatterer where effects due to the beampattern are isolated. The other geometries include partitioning the echoes according to whether they are all within a patch, spanning the edge of one patch, and spanning multiple patches.

This partitioning and associated analysis, which has not been done in previous studies, leads to new insight into how to account for beampattern effects when patches of fish (or, more generally, patches of any type of scatterer) are present when using a directional sonar [31]. The results apply directly to short-range direct-path sonars and provide valuable information on the fish-echo component of long-range sonars without the complicating effects of the ocean waveguide [20]. Furthermore, although the results involve only one type of fish observed in a particular location and at a particular time, the measurements are controlled and isolate important elements of the statistics and associated general equations which, in turn, can be applied to other fish at other locations and times for similar cases of isolated fish and patches of fish. For example, this study concerning single-species, single-size fish, now observed in isolation, can be extrapolated through the general equations to multiple species, multiple sizes. Also, a "patch," defined and discussed in more detail later, is defined, in part, relative to the resolution of this particular sonar, the grouping of fish on scales larger than the resolution, and the abruptness of the patch edge. Although the analysis is specific to these particular data, the results can be applied to other sonars and patch sizes provided the patches have similarly abrupt edges and that their sizes are similarly larger than the sonar resolution cell.

Comparisons with theoretical pdfs are made, some of which are explicitly connected to the scattering physics and sonar parameters over a broad range of conditions, and the other being the K-distribution [35]. The K-distribution is applied as it has not only been shown in previous studies to be very useful in predicting the statistics of various reverberation processes, but it can also be connected, to a much more limited extent, to parameters of the scattering and sonar [20], [21].

II. Experiment and Partitioning of Echo Data

Acoustic backscattering data from individual fish and patches of fish were collected during a ten-day annual survey of Atlantic herring in 2005. The survey was conducted by the Northeast Fisheries Science Center (NEFSC), National Oceanic and Atmospheric Administration (NOAA), over Georges Bank off Cape Cod, MA, using the *FR/V Delaware II*. Samples of fish were collected with a pelagic trawl. A modified form of an Edgetech broadband acoustic system was towed in water depths of 190–215 m at a speed of about 2.5 kn and is described in [30]. The system was towed over the fish at a range of approximately 30 m to the fish. There was no evidence from the data that towing at this range caused a change in behavior of the fish. One of the three acoustic channels spanned the frequencies 1.7–10 kHz (most energy in the 2–4-kHz band) and data collected during two transects during the day will be the subject of this analysis. The beamwidth in this band was in the range 23°–47°. All data analyzed are from the echo envelopes after pulse compression processing. With a range resolution of the processed signal at approximately 20 cm, the sonar resolution cell at this range of detection and beamwidths was approximately 40 m^3. The net samples show that the fish were generally monospecific (herring) and nearly monosize (average length of 23.6 cm; standard deviation = 1.7 cm). The acoustic data in the lowest frequency channel show the fish when residing near the bottom at these depths to have a strong resonance at 3.7 kHz as a result of the gas-filled swimbladder resonating [30]. Also, the numerical density of the fish varied from patch to patch, but was no higher than 2 m^{-3} [30].

Two different types of data are analyzed, one in which the numerical density of the fish is low compared with the sonar resolution and the individual fish are resolved (Fig. 1), and the second in which the densities are much higher relative to the sonar resolution and they are not resolved (Figs. 2 and 3). In this latter case, the fish are shown to be aggregating in patches of varying size.

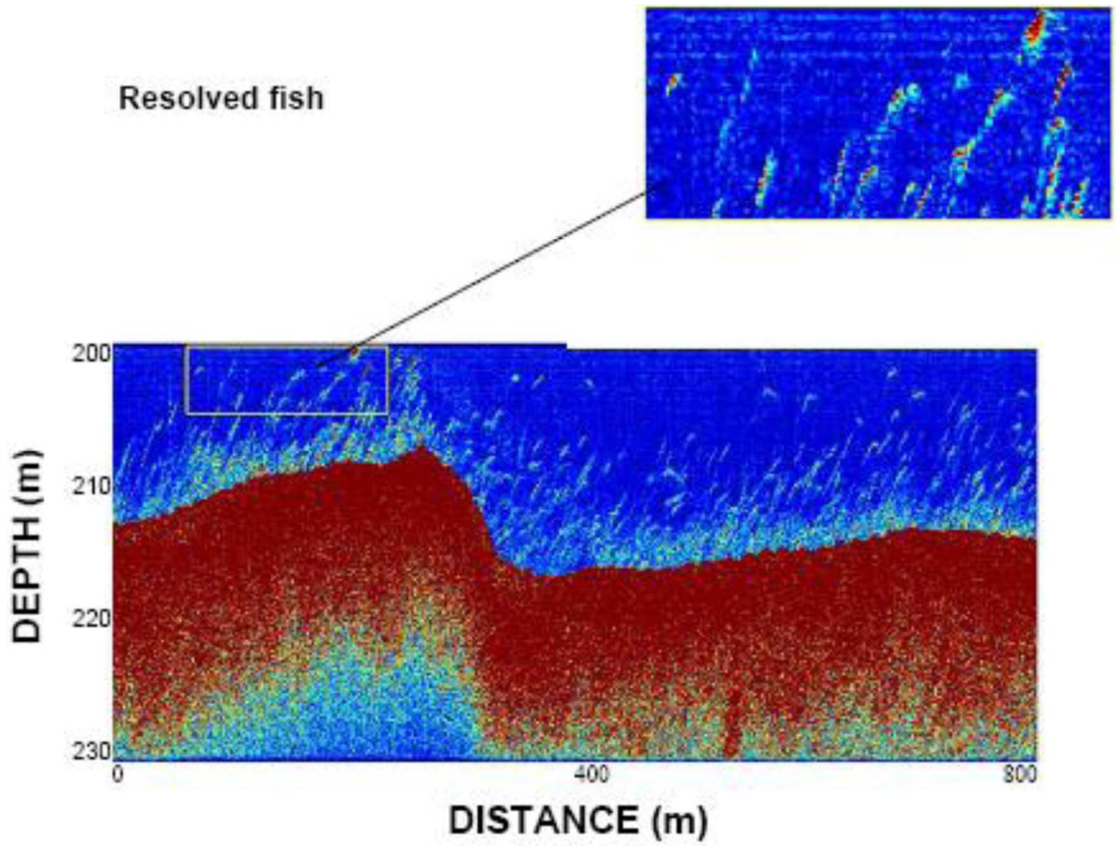

Fig. 1. Echogram of resolved individual fish, as collected in the 2–4-kHz band. The box corresponds to the window in which the statistics were analyzed.

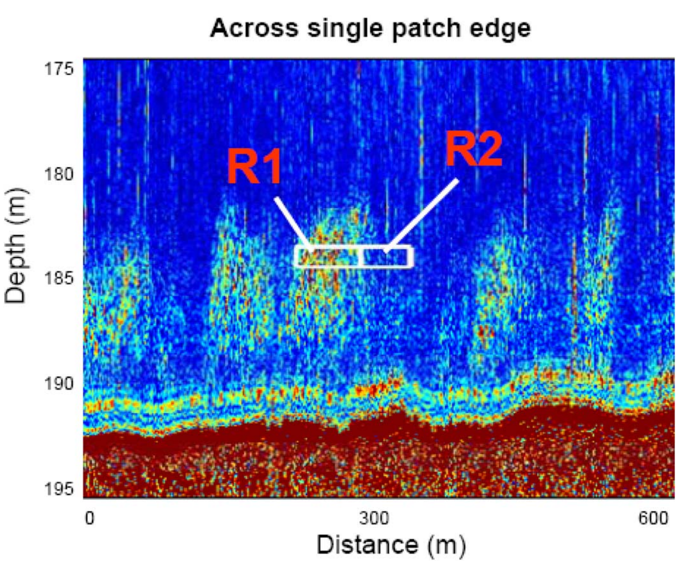

Fig. 2. Echogram involving patches of unresolved fish, as collected in the 2–4-kHz band. The outer white box outlines a region where the sonar beam sweeps across a single-patch edge. The box is divided into two inner regions: R1 involving the beam being within a patch and R2 involving the beam being outside the patch. The statistics of the echoes are analyzed for each of these windows (R1, R2, and R1 + R2).

A. *Defining Patches*

Patches are defined in the context of this research by a combination of the acoustic parameters and behavior of the fish. Specifically, for this particular experiment, the "patches" of fish were observed to be associated with a contiguous group of echoes due to unresolved fish in a multiping sequence whose levels were well above the background noise level. "Contiguous" refers to echoes from adjacent pings as well as within the time series of the echo from an individual ping. Visually, and hence, qualitatively, the resultant patterns of fish echoes in the echograms have the *appearance* of groups or patches of fish. These patterns depend upon a combination of spatial distribution of the fish and resolution of the sonar. Quantitatively, there is a relatively abrupt change in acoustic level at or near the edge of the patch, from high (but finite) signal-to-noise ratio (SNR) within the patch to background noise outside the patch. The SNR in this application is typically 10–15 dB, with the modes (maximum value of pdf) of the echo statistics of the fish echoes and background noise clearly separate. Since the SNR is finite, part of the "fish" echo contains background noise. The result of a finite SNR is a slight "whitening" of the fish-echo data, causing any non-Rayleigh characteristic to tend slightly toward Rayleigh. This type of grouping behavior of fish was observed many times during the experiment. There were also cases in which the fish were not grouped in patches, but rather in a much more diffuse manner where there was not a clear edge. These latter cases were not considered for this analysis.

Although the definition of fish patch used in this paper contains the resolution of the sonar (as opposed to containing parameters solely associated with the fish), it is also directly relevant to the subject of this paper—echo statistics according to

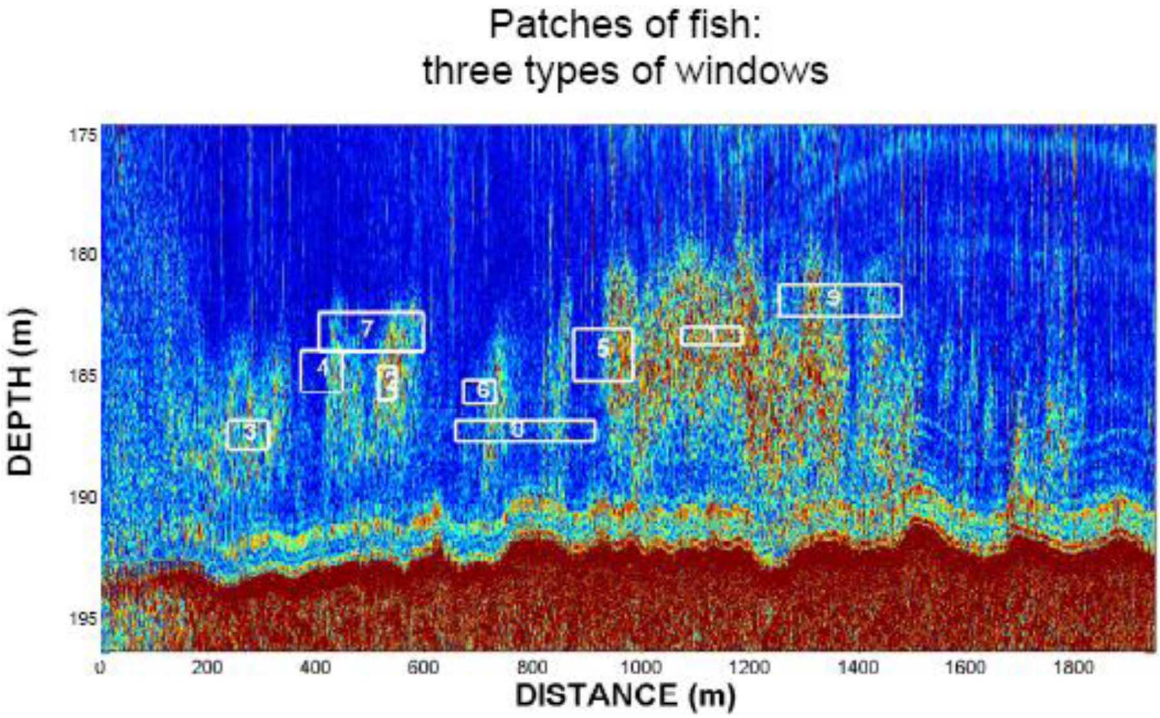

Fig. 3. Echogram involving patches of unresolved fish, as collected in the 2–4-kHz band. The nine white boxes correspond to windows in which the statistics were analyzed. The boxes span three types of conditions: boxes 1–3: sonar beam remains within a patch; boxes 4–6: sonar beam sweeps across a single-patch edge; and boxes 7–9: sonar beam sweeps across multiple patches.

sonar resolution. As discussed in the papers cited earlier in this paper and as shown below, the echo statistics are a strong function of patch size relative to sonar resolution cell. For example, if a narrow beam sonar is moved close enough to an aggregation of fish, it is possible that it might resolve the individual fish. The echo statistics associated with resolved individual scatterers are significantly different from the statistics associated with unresolved scatterers. Thus, it is essential, in the context of studying echo statistics, to incorporate sonar resolution in the definition of patch.

Finally, in the data analysis, categorizing patches with the above definitions was subject to error simply because fish generally do not organize perfectly into clear, distinct dense groups with distinct boundaries. For example, the "edge" of the patch was sometimes not perfectly contiguous resulting in a fragmented appearance. In this case, classifying the patch was somewhat subjective and sometimes a portion of a fragment was considered to be part of the larger patch that it was near. Also, sometimes in the sections considered to be between patches, there were occasional echoes from individual fish. Again, classifying the between-patch section as such was somewhat subjective. To conclude, because of the finite density of fish and natural behavior, there was contamination of the fish echo with background noise, contamination of the "between patch" data with fish echoes, and error in definition of patch boundary since the edges were not perfectly sharp.

In general (i.e., beyond the data collected in this experiment), fish exhibit a variety of grouping behaviors, as reviewed in [22]. The analysis specific to these data can be applied, through the methods summarized below, to other fish and other sonars, subject to the aforementioned criteria involving contiguous grouping (as observed by a sonar with a given resolution cell) and distinct patch edge.

B. Forming Histograms of Echo Data

The statistical properties of the echoes are studied within the windows shown in Figs. 1–3. The patch analysis in Fig. 2 focuses on one specific case: the sonar beam sweeping across a single-patch edge. The data window is designed so that the statistics associated with the sonar beam being within the patch (R1) and outside the patch (R2) can be studied separately before being combined (R1 + R2). There are nine windows in Fig. 3, three per category: all data within a single patch, data spanning across one edge of a patch, and data spanning across multiple patches.

Histograms were formed from the windows and compared with theoretical pdfs (Figs. 4–6). Histograms were created using echo data from tens to hundreds of pings sampled at the Nyquist rate (a rate based on transmit signal before transducer effects) creating up to thousands of points per plot. Because of the reduced bandwidth of the signal caused by the frequency-dependent transducer response, the number of statistically independent samples within a window is in the low hundreds to well over 1000, depending upon the window size, with the smallest window (low hundreds of points) being within the limit of being statistically valid for these broad distributions. Here "statistical independence" involved either insonification of 1) completely different set of scatterers such as in the case of the data being from the same ping, but separated in time by greater than an inverse bandwidth or in the case of the data being from pings separated by a distance greater than an acoustic footprint or 2) overlapping set of scatterers,

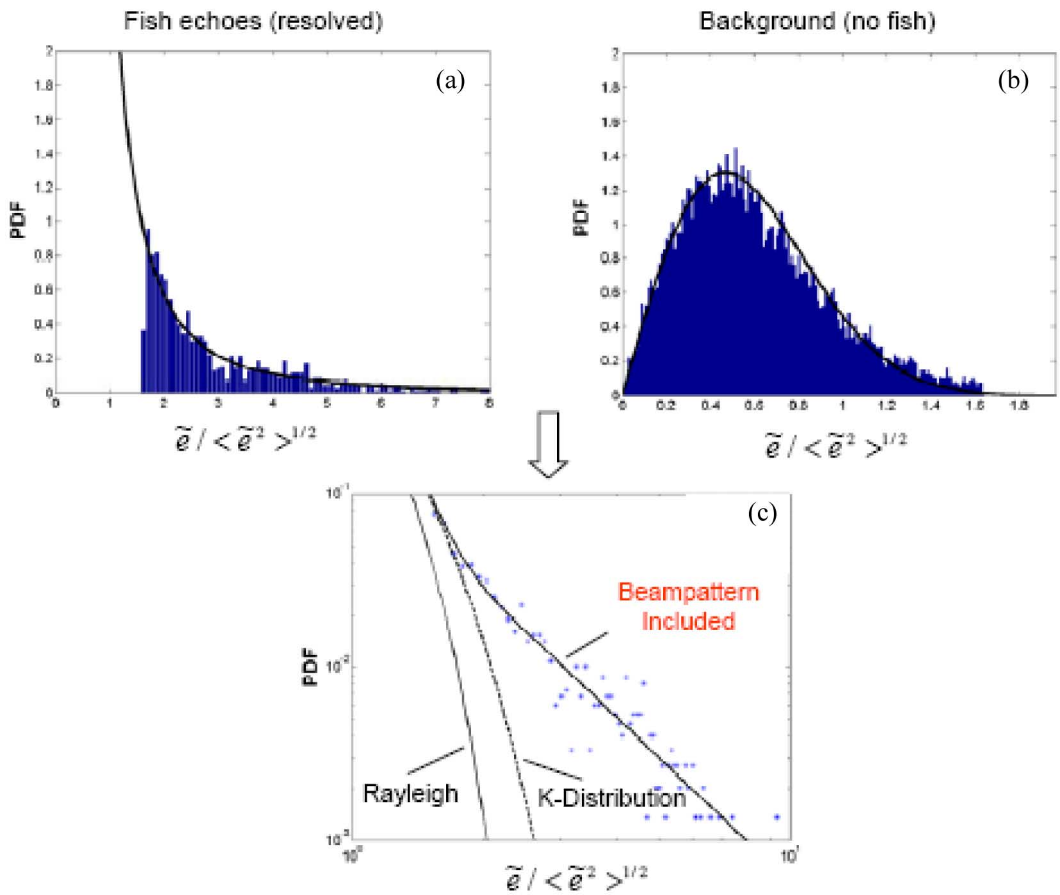

Fig. 4. Echo statistics associated with resolved fish from Fig. 1. (a) Fish echoes above a threshold with (2) superimposed. (b) Background noise below the threshold with the Rayleigh pdf superimposed. (c) All data combined with the mixed pdf given in (1) superimposed.

but with completely different phases (randomly and uniformly distributed over the range 0–2π) such as in the case of data from adjacent pings at the same range. Being "statistically valid" requires that samples needed to be large enough so that the parameters of theoretical pdfs could be determined satisfactorily. Although it is ideal to maximize the number of samples to conduct a statistical analysis, it would be at the expense of stationarity for such a patchy environment. Thus, determination of window size involved a tradeoff between number of statistically independent points (where a larger window provides a more desirable number of points) and statistical stationarity (where a smaller window better ensures stationarity in a patchy environment).

III. Statistical Analysis

The statistical analysis is divided according to whether the echoes involve resolved fish or patches of unresolved fish. The case of patches is further divided into whether the sonar beam remained within a patch, spanned across a single edge of a patch, or spanned multiple patches. In all cases except for when all echoes are from within a patch, a mixed pdf will be used to analyze the data. The "mix" in this case occurs when data involving system noise between fish echoes are included in the analysis. The mixed pdf is given as

$$p_m(\tilde{e}) = (1 - A_r)p_N(\tilde{e}) + A_r p_F(\tilde{e}) \qquad (1)$$

where $\tilde{e}$ is the echo envelope as measured through the receiver of the sonar, $p_N(\tilde{e})$ is a Rayleigh pdf describing the background noise measured between the fish or patches, and $p_F(\tilde{e})$ is the pdf describing the echoes from the individual fish or patch.

The parameter A_r is a weighting factor in the range 0–1 that is determined by the ratio of the aggregate number of samples associated with fish echoes to the total number of samples in the selected window. The samples associated with fish echoes were determined initially through a visual inspection of the echograms and identifying what portions of each echo was associated with fish, as described in the previous section. From that information, the relative number of samples of fish echo and noise-only (no fish) were determined. In this approach, the fish echoes were approximately 10–15 dB higher than the background noise. Since the resolution of the sonar is much smaller than the extent of the fish distribution in all three dimensions, the echograms represent a 2-D "slice" (of finite, but small, thickness) at an arbitrary angle and arbitrary location through the 3-D distribution of fish. The term A_r thus represents, in essence, the "area" in this slice associated with fish echoes relative to the total "area" sampled.

The mixed pdf given in (1) only involves two components: one associated with the fish echo and the other associated with the system noise between echoes. This is based on the fact that the fish are all of a (nearly) single size and single species, as determined by net sampling and by resonance classification (showing the swimbladder resonance to be the same throughout

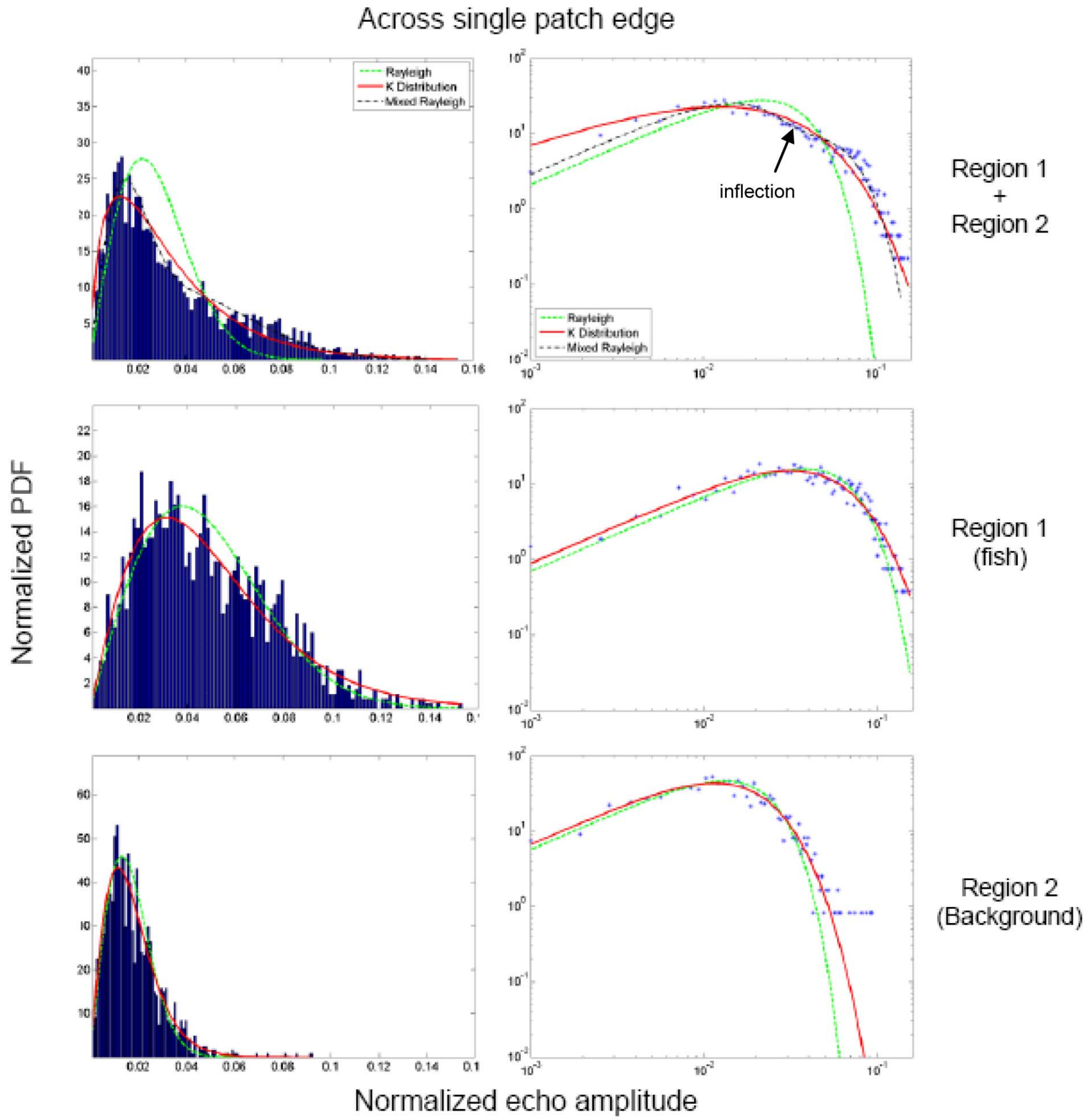

Fig. 5. Echo statistics associated with data from a single-patch edge in Fig. 2. Both linear (left column) and logarithmic (right column) scales are shown.

the patches) [30]. This relatively simple composition of fish, in combination with the relatively well-defined patches, allowed use and testing of the relatively simple two-component mixed pdf.

In more complex assemblages, a higher component mixed pdf would need to be considered. For example, if there was a broad distribution of sizes and/or species of fish within a patch and if each size class or species was well populated with many per sonar resolution cell, then a one-component pdf would be appropriate for data within the patch, resulting in a combined two-component mixed pdf for the combination of fish echoes and between-patch noise data as in this current analysis. However if, for example, there were many small fish per resolution cell and a sparse distribution of large fish (fewer than one per resolution cell) within a patch, then a two-component mixed pdf would be required for the patch alone, resulting in a three-component mixed pdf for the combination of fish patch and between-patch data. Examples are given in [1] of the statistics of echo data associated with 1) mixed assemblage of sparsely distributed fish (fewer than one per sonar resolution cell), where there are two distinctly different sizes of fish, and 2) a patch involving a mixed assemblage of densely distributed small organisms (zooplankton) and sparsely distributed large fish within the patch.

A. *Resolved Fish*

In [36], a simple expression was derived describing the echo statistics from resolved identical scatterers randomly located in the mainlobe of a directional sonar beam, where the scattering amplitude of the scatterer is delta function distributed

$$p_F(\tilde{e}) \simeq k_0\, \tilde{e}_0^{\gamma-1} \tilde{e}^{-\gamma}, \qquad b_{\mathrm{SL}} \leq b \leq 1 \qquad (2)$$

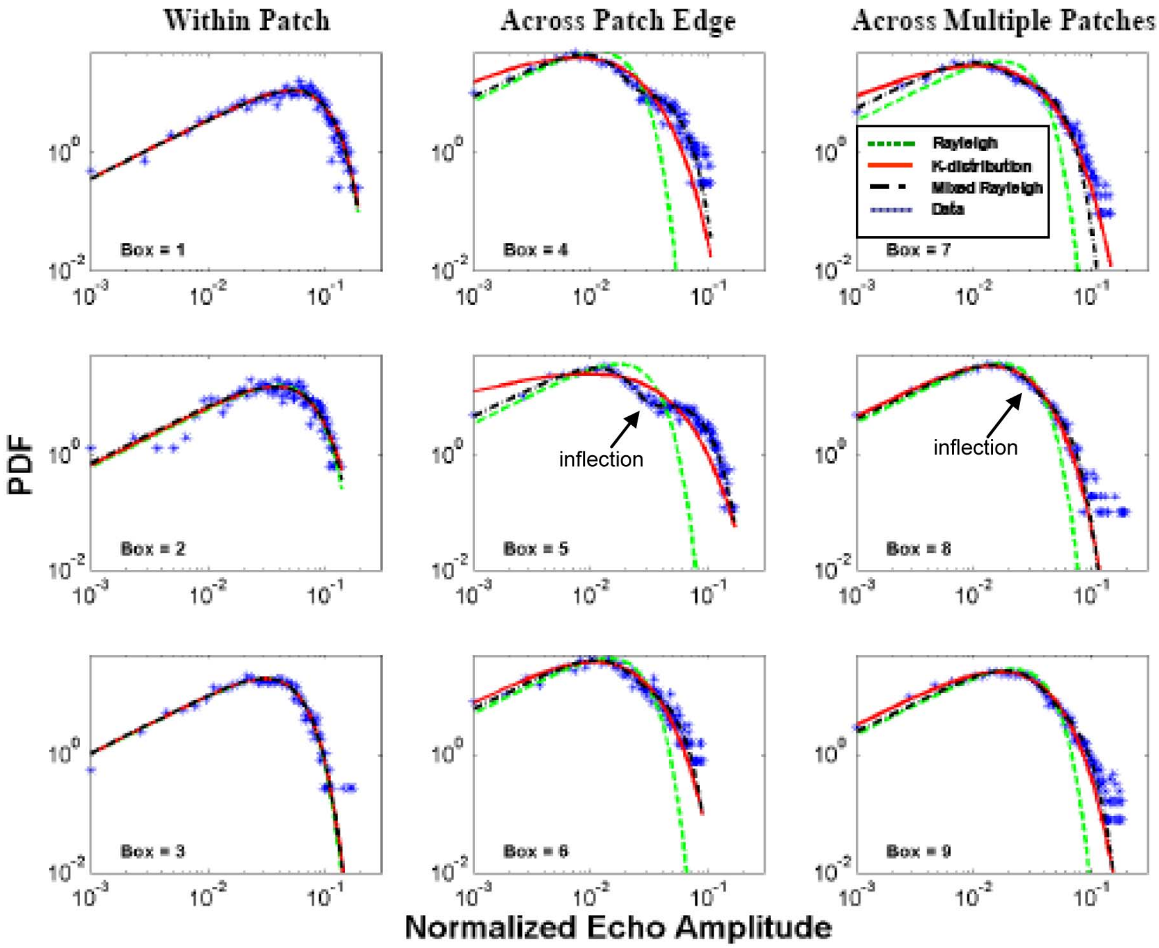

Fig. 6. Echo statistics (pdf) associated with patches of fish from Fig. 3.

where k_0 is a constant and is determined so that the integral of p_F over $\tilde{e}$ is unity ($k_0 = (1-\gamma) b_{\rm SL}^{(\gamma-1)} (b_{\rm SL}^{(\gamma-1)} - 1)^{-1}$), $b_{\rm SL}$ is the value of the highest sidelobe of the composite (two-way) directivity pattern of the sonar (where $b = 1$ in the center of the mainlobe), γ is the magnitude of the slope of the tail of the beampattern pdf on a log–log plot (i.e., for $b > b_{\rm SL}$), and $\tilde{e}_0$ is the (constant) scattering amplitude (i.e., before beampattern effects) of a single scatterer. This approximate expression applies to a directional sonar in which the scatterer is randomly located in the mainlobe at points in the beam higher than the highest sidelobe, as indicated by the inequality. Because of this condition, the expression applies to the higher values of the echoes, that is, the "tail" of the echo pdf. Since directionality was assumed in the derivation, the equation does not apply to the simple case of an omnidirectional beam where $p_F(\tilde{e}) = \tilde{e}_0$. Also, since γ is always positive, the slope $(-\gamma)$ of the pdf is always negative.

This equation is applied to the case under investigation involving scattering at resonance of nearly same-sized fish which results in the scattering being narrowly distributed. With this narrow distribution of scattering amplitudes, the echo distribution, as measured through the sonar, is approximately equal to the beampattern pdf. This is in contrast to more complex forms of the equation when the scattering amplitudes were broadly distributed, as reviewed in [36]. Equation (2) is written in approximate form and shows the echo distribution to be approximately a power law at the higher values of echo level (i.e., values of echo level corresponding to the scatterer occurring solely in the mainlobe of the beam and at positions in the beam where the mainlobe value is higher than the highest sidelobe). Although the expression was derived for the composite pattern associated with a piston transceiver (conical beampattern), it also applies to the data in this study where the composite pattern is approximately conical, but dominated by the narrower receive beampattern (the transmitter has a wide beampattern).

Application of (2), in combination with (1), to the resolved echoes in Fig. 1 shows a superior fit to the data compared with using a Rayleigh distribution or a K-distribution (Fig. 4). A key aspect to the data is the very high tail, due to beampattern effects, which is explicitly accounted for in (2). Here, the data are presented two different ways: the fish echoes $p_F(\tilde{e})$ above a threshold are given in Fig. 4(a), with (2) superimposed. Although this was originally a very broadband signal resulting in a frequency-dependent beamwidth, it was bandpass filtered. An intermediate value of frequency corresponding to near the peak of the spectrum was used in $\gamma(= 1.2)$ in (2), although at these beamwidths, γ is nearly independent of frequency [36]. The scattering amplitude $\tilde{e}_0$ in (2) was removed from the calculations through normalization (x-axis). The background noise $p_N(\tilde{e})$ not involving fish is given in Fig. 4(b) with the Rayleigh pdf superimposed. The two sets of data are combined in Fig. 4(c) with the mixed pdf given in (1) superimposed. Here, A_r and the means of p_N and p_F in (1) were determined directly from the data. A_r was determined according to the threshold determined by the noise background as described above. Since the echo amplitudes are normalized by their root mean square (rms) value, the two-parameter K-distribution reduces to a one-parameter distribution and the distribution was fit to the data by a least squares approach by varying only one (shape) parameter. In this case, the one-parameter Rayleigh distribution reduces to a zero parameter distribution and the distribution is plotted directly with no fitting process.

B. Patches of Unresolved Fish—Three Geometries

Three geometries are studied: 1) sonar beam remains within a patch, 2) sonar beam sweeps across the edge of one patch, and 3) sonar beam sweeps across multiple patches (Figs. 5 and 6). For all of these cases, $p_F(\tilde{e})$ in (1) is assumed to be a Rayleigh pdf due to echoes from unresolved fish that arise from within each patch and $p_N(\tilde{e})$ is a Rayleigh pdf due to noise measured outside or between patches. The assumption that p_F is a Rayleigh pdf is based on the fact that the data were generally Rayleigh or close to Rayleigh. This analysis was not restricted by that assumption had there been few enough fish in a resolution cell for the echoes to be non-Rayleigh. The least squares fit of the K-distribution to the data, as well as calculation of the Rayleigh distribution (no fitting), were done the same way as described in Section III-A.

For the simple case of all echoes being within a single patch, then only one component $(p_F(\tilde{e}))$ contributes to the variability of the echo, resulting in a simple (not mixed) Rayleigh distribution. Once the sonar beam passes across the edge of a single patch or across multiple patches, the resultant distribution includes echoes from both within and outside the patch and is strongly non-Rayleigh as described by the mixed Rayleigh pdf. In all of the cases involving non-Rayleigh echoes, the largest deviations from the Rayleigh distribution occurred in the tails of the pdfs as illustrated in Figs. 5 and 6. The cumulative distribution functions (cdfs) did not contain significant information regarding the deviations (not shown).

The case of the sonar beam sweeping across a single-patch edge is studied in detail in Fig. 5. In the top row, the echo statistics associated with all data, including the sonar being both within and outside the patch, is illustrated. In the second and third rows, data from the respective sections, within the patch (second row) and outside the patch (third row), are analyzed. Data of similar type (within patch only, outside patch only) are shown to be approximately Rayleigh distributed, differing only in the means. The mean of the pdf associated with being within a patch is much greater than that associated with being outside the patch. Once the data from the two data types are combined, a mixed Rayleigh distribution best describes the data (top row). Here, the two Rayleigh pdfs used to model the data are formed according to the relative value of the means of the two separate windows. The parameter A_r was determined according to the relative proportion of samples insonifying each window. A distinct feature of the data and theoretical mixed Rayleigh curve is the inflection in the data/curve just past the mode (maximum value of pdf) of the data/curve, as indicated by the arrow. The predicted mixed pdf (dashed black line) coincides very well with the data at and near the inflection and is hidden by the data in this portion of the plot.

The case of the sonar beam sweeping across a single-patch edge is further studied in the middle column of Fig. 6, where the results are summarized for three different data windows (all involving a single edge). In each case, a mixed Rayleigh pdf best describes the data, with the parameters being determined directly from the data as in Fig. 5. The inflection in the data/curve, as also observed in the case above for Fig. 5, is particularly pronounced in the middle row of this middle column (panel associated with box 5) and is indicated by an arrow. Here, the edge of the patch is relatively sharp compared with the other edges analyzed, causing the distinct inflection (which is nearly a dip).

Although the mixed Rayleigh pdf is shown to best describe all single-edge data, the K-distribution provides a reasonable fit (via least squares method as in Fig. 4) for echo values higher than the mode (Figs. 5 and 6). In these examples, the K-distribution does not predict the inflection, but rather passes through intermediate values of the structure.

Once the sonar beam sweeps across multiple patches (and, hence, multiple edges), the inflection in the data/curve beyond the mode is still present although much less pronounced. In this last case, the mixed Rayleigh pdf remains the best function to describe the data compared with the pure Rayleigh distribution and K-distribution. However, the improvements of the fits with data using the mixed Rayleigh over the K-distribution are smaller in the case of multiple patches versus the case of a single-patch edge.

In this latter case involving multiple patches, the mean backscattering strength varied from patch to patch. Because of the variability, ideally there should be a different Rayleigh pdf (that is, each one with a different mean) for each patch. However, it was determined that use of a simple two-component mixed Rayleigh pdf (one for the background noise and only one to collectively describe all patches) could satisfactorily fit these data, provided that the best fit criterion was used with the two parameters (A_r and the mean value of scattering strength) determined empirically.

C. Distances Between PDFs and Discrimination

An important element in analyzing statistical data is determining the best means by which the data can be discriminated. Toward this goal, "distances" between the observed and theoretical pdfs were calculated through two different standard methods and several combinations of data and theory (Fig. 7). One method is based on the standard L_2 criterion (similar to the conventional least squares) and the other is based on the quantity proposed by Kullback and Leibler in [37], termed the KL distance.

L_2-norm

$$Q_{L_2} = \sqrt{\sum_i [p_{\rm data}(x_i) - p_{\rm model}(x_i)]^2} \tag{3}$$

KL distance

$$Q_{\rm KL} = \sum_i p_{\rm data}(x_i) \log\left[\frac{p_{\rm data}(x_i)}{p_{\rm model}(x_i)}\right] \tag{4}$$

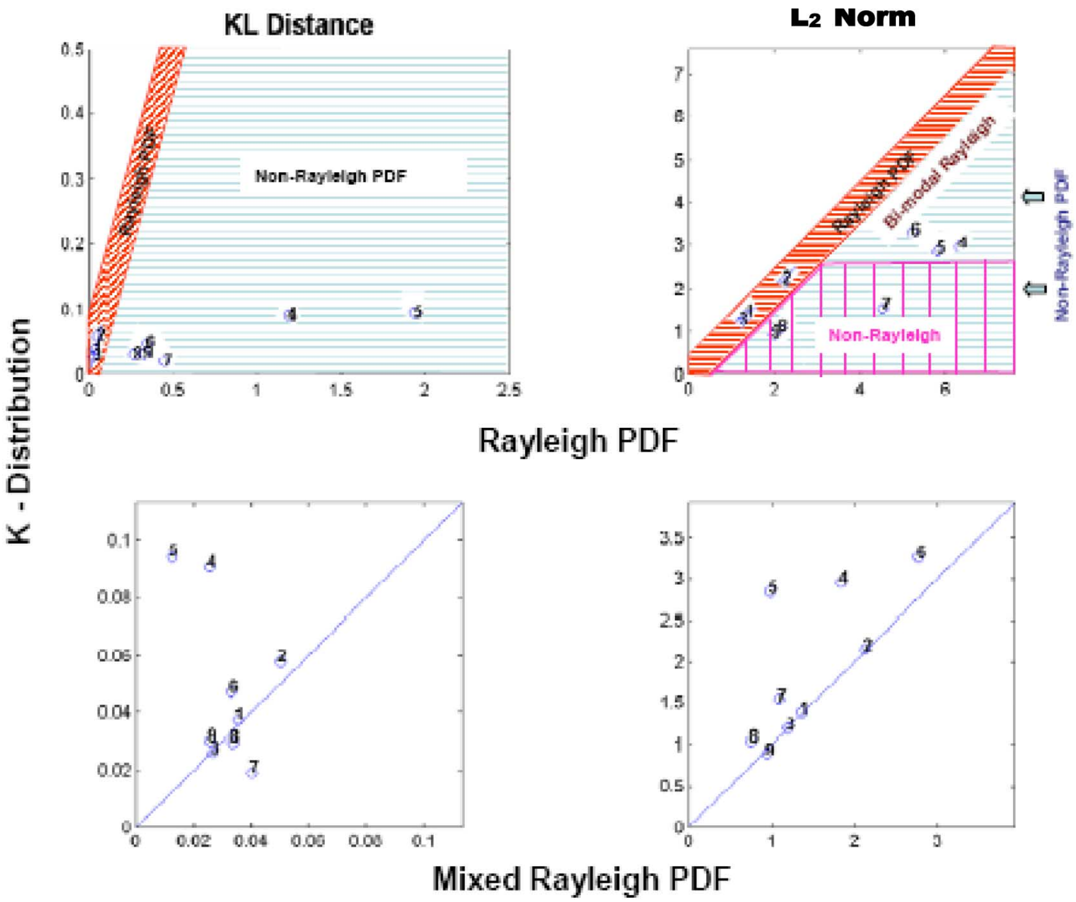

Fig. 7. Distances between various theoretical pdfs and data from Fig. 6, as calculated through two methods: KL-distance and L_2-norm distance. The line in each plot has a slope = 1 to delineate differences between use of the different theoretical pdfs. The numbers correspond to the data associated with each box in Fig. 3 (and modeled in Fig. 6).

where Q_{xx} is the distance for each method, and $p_{\rm data}$ and $p_{\rm model}$ are pdfs of the data and model, respectively. The L_2-norm focuses on the overall mismatch between the data and the theoretical models with even weights, while the KL distance, in addition to the overall mismatch, emphasizes the mismatch between the tails of the pdfs because it involves logarithms. The KL distance can be related to the Boltzmann entropy and has also been called the KL discrepancy, divergence, information, and number [38]. By setting appropriate thresholds to distinguish between Rayleigh and non-Rayleigh distributions, we can construct simple fish echo discriminators.

The distances plotted in Fig. 7 are calculated for each of the nine data windows illustrated in Fig. 3 and used in direct comparisons with theoretical models in Fig. 6. The left panels involve the KL distance and the right panels involve the L_2-norm. All vertical axes involve distances calculated relative to the K-distribution. The horizontal axes of the top and bottom panels involve the Rayleigh and mixed Rayleigh pdfs, respectively. In each panel, a line with a slope of unity is drawn to help delineate distances that are different when calculated for the different types of pdfs.

In all cases, the data from within a patch (windows 1–3 in Fig. 3) fall on the "slope = 1" line. This is because those data are Rayleigh distributed, and the limiting cases of the K-distribution involving the equivalent of an infinite number of scatterers and the mixed Rayleigh distribution (setting $A_r = 1$) becoming a pure Rayleigh distribution best fit the data. In the other windows (windows 4–9 in Fig. 3), the distances generally deviate from the "slope = 1" line and, in some cases, significantly. Here, "significantly" relates to the fact that the distances are much greater than the window-to-window variability measured in the Rayleigh windows (1–3). In the upper two panels, the distances calculated in those six windows are smaller for the K-distribution than for the Rayleigh distribution indicating that the K-distribution is the better fit of the two. In the lower two panels, the distances calculated from windows 4–6 (single-patch edge) are smaller for the mixed Rayleigh than for the K-distribution, indicating that the mixed Rayleigh is the better fit of the two for that particular scattering geometry. Once the sonar beam spans multiple patches (windows 7–9), the distances in the lower two panels are close to the "slope = 1" line, indicating that both the K-distribution and mixed Rayleigh pdf are nearly equally good at describing the non-Rayleigh behavior of the data in this geometry.

Finally, the range of KL distances tends to be much larger than the range of L_2-norm distances (on a relative scale) in the upper two panels. This difference indicates that the KL distance can discriminate between the non-Rayleigh data and the Rayleigh pdf much better than the L_2-norm. This discriminating property of the KL distance is because the significant differences between the Rayleigh and non-Rayleigh data principally occurred in the tails and the KL distances involve a logarithm, which emphasizes the tail over the L_2-norm whose distances are on a linear scale.

IV. Summary and Conclusion

The statistics of fish echoes in a short-range, direct-path scattering geometry have been studied in an ocean experiment over a range of scattering geometries involving resolved fish, unresolved fish in patches, and the sonar beam sweeping across patch edges. New insight in the problem has been developed with the acoustic frequencies involving the resonance frequency of the fish and with the partitioning of echoes relative to the boundaries of patches of fish. With the fish scattering as monopoles at these frequencies (principally 2–4 kHz) and having a narrow size distribution, effects of the beampattern on the echo fluctuations have been isolated for the first time. Furthermore, through partitioning the echo data, effects on the echo statistics of sweeping across a patch edge and across multiple patches could be quantified and compared with data arising solely from within a patch.

Two-component mixed pdfs were used to describe all data. 1) In the case of resolved fish, the mix involved the sum of the beampattern pdf and the Rayleigh pdf from noise between fish echoes. Since the (resonant) fish echo pdf (not including the beampattern pdf) was approximately a delta function pdf, this analysis was the first direct (i.e., without compounding effects) experimental confirmation of the use of the beampattern pdf to predict sonar echo pdfs. 2) In the case of sweeping across patches (single-patch edge and multiple patches), the mix involved the sum of two Rayleigh pdfs: one from the fish patch(es) and one from the noise between the patches. Since all fish were observed, through use of nets and resonance frequency analysis, to be the same size and species, only a two-component mixed pdf was required in each of the cases (resolved and unresolved), which simplified the analysis and allowed for much control over the parameters of the predictions of the pdfs. The modeling elements of this analysis can be applied, in principle, to more complex assemblages such as involving multiple size classes of fish, which may result in a mixed pdf with more than two components.

The mixed pdfs best described the data in both 1) and 2) above because of the fact that parameters of the pdf were based on the physics of the scattering and sonar parameters. However, it was also determined that the K-distribution was a reasonable fit to the data involving patches even though the connections to the physical parameters are not as explicit and are much more limited, and, as the complexity of the data window increased from the sonar beam sweeping across a single-patch edge to sweeping across multiple patches, the quality of fits to the data of the mixed Rayleigh and the K-distribution became essentially the same. Thus, this study demonstrated that, although the K-distribution was not the optimum distribution, it is a reasonable distribution to use as an alternative, especially if the patch structure is unknown and the (physics-based) mixed pdf cannot be constructed directly from the data.

In addition to characterizing the statistics, they were also discriminated through two different approaches that were logarithm based and linear based. The non-Rayleigh data were best discriminated from Rayleigh pdfs through use of calculations that emphasized the tail of the distributions (KL), which is logarithm based, since the non-Rayleigh nature of the data appeared principally in the tail.

Challenges in the analysis involved the following: 1) definition of a patch which was somewhat subjective in nature, especially since the fish-echo-to-background-noise ratio was finite and the "edges" of the patches were sometimes fragmented; and 2) choosing sampling windows that were large enough to allow enough statistical samples but not so large as to violate stationarity in a patchy environment. Given the variable nature of fish distributions, as documented in the citations in this paper and as observed in this study, both of these challenges should generally be expected in analyzing any data involving fish.

Although these data involved one species of one size sampled in one location during a short period of time, the analysis was conducted in a controlled manner so that the results could apply to other fish in other locations and times. Specifically, the control in the analysis involved identifying patches that were relatively distinct (as opposed to diffuse layers with poorly defined boundaries). The fish inside the patches were unresolved, resulting in Rayleigh or Rayleigh-like echoes. Between patches, there were either no fish or few enough fish so as not to alter the outcome. The resolved fish had distinct strong echoes. Whether the fish were resolved depended upon the particular resolution of this sonar at these ranges relative to the density of the fish. In order for these results to be applied to other fish at other locations and times, similar *generic* conditions must be followed concerning resolution of sonar relative to density of fish, as well as distinct nature of patches (reasonably well-defined edges). Confirmation of the beampattern effects in this study for this particular sonar gives confidence in the equations and that they can be applied to sonars with different beamwidths.

Finally, this study was specific to direct path sonars. The results are directly applicable to any short-range sonar, including those used to study fish. As reviewed in [1], statistics of resolved echoes can be used to estimate numerical density of fish and classify fish according to differences in gross anatomical features such as length. The transition between non-Rayleigh statistics and Rayleigh statistics as the density of fish relative to sonar resolution increases can be used to directly estimate numerical density at that transition region [1], [12].

Although echo statistics associated with long-range sonars is out of the scope of this study as it involves the effects of the ocean waveguide on the acoustic signal, in principle, the results can be extrapolated to that ocean waveguide application. For example, in [20], the effects in the statistics of echoes were studied as the echoes experienced multiple paths within the ocean waveguide. Parameters of the statistics (K-distribution) were shown to change with increasing number of paths in the echo as the distribution "whitened."

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