Acoustic Signatures of Birds, Bats, Bells, and Bearings

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ABSTRACT

The acoustic signatures of Birds, Bats, Bells, and Bearings have much in common. There are also subtle differences. "Bird Watchers" have the uncanny ability of identifying unseen birds by the sounds (and songs) they produce. The ability to distinguish between different types of birds by the sounds they make is equivalent to being able to announce the condition of an operating bearing after listening to it. One example is the fact that for many years now railroad track maintenance workers have been able to identify defective roller bearings on-the-fly, as they pass, even at speeds of 30 to 50 MPH. [Reference 1]

The unique features of sounds produced by both biological and mechanical systems provide many clues for future diagnostic implementation. Although we cannot fully imitate the diagnostic capability of the human brain, we can build computerized detection systems that take advantage of some ways the brain quickly identifies common sounds we hear everyday [Refs. 1-18].

This paper (and its accompanying acoustic presentation) explores the similarities, as well as, the differences of actual signals collected from Birds, Bats, Bells, and Bearings. This topical review paper also explores some of today's analytical processing methods available for determining the differences in the conditions of operating bearings.

INTRODUCTION

Anyone who attempts to relate the topics contained in the paper title may expect to either find very little or uncover some surprising facts. Before reviewing these diverse topics the author himself wasn't sure. However, as data was collected and the review continued it was clear that there are many similarities and much to learn from the acoustic outputs of these biological and mechanical sources. Let's take look at some bearing data first.

Some of the most common bearing defects and their frequency of occurrence are listed in Table 1. Not all applications will provide these numbers but they are typical. It must be noted that 46% of these defect types (the sum of the top two and the last one) may provide no vibration at all. Furthermore, it might be expected that these bearing conditions could provide an infinite variety of vibration signatures allowing no general statement about their character – much less afford a comparison with other vibration and acoustic generating sources.

Table 1 Top 10 Bearing Defects by Defect Type

Defect Type	%	Cum
Lack or Improper Lubrication	26	26
Loose or Improper Bearing Mount	17	43
Single Spall - Outer Race	12	55
Cage Defects	10	65
Multiple Spalled Outer Races	9	74
Single Spall - Inner Race	8	82
Multiple Spalled Inner Races	7	89
Damaged Balls or Rollers	5	94
Contaminated or Erroded Surfaces	2	96
Other Misc Defects	4	100

One way in which data from a variety of bearings can be associated is through statistics [Ref. 2-3]. Figure 1 below displays this fact in a simple way. Bearings from each defect class listed above are included in the figure. The data from each bearing is shown with a separate symbol in the plot. Although all defects are different the trends for each is similar. The common feature for each is that the "standard deviation" of the time based signature is proportional to bearing speed – some more highly sloped than others, but all positively upward with higher speed.

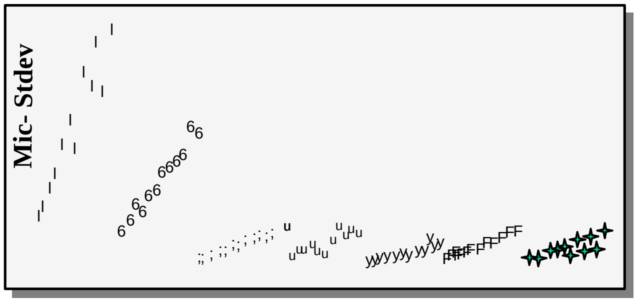

Figure 1 Seven Bearing Defect Types Show a Common Trend

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Each bearing's output is plotted against the same identical variation in speed, but in this case, the data has been clustered by bearing defect type to see their individual trends.

The example of Figure 2 shows one reason why each of the defect types maintains the trend with speed that it does. The figure below shows an acoustic output from a bearing as the bearing coasts down in speed. The peak amplitude of this inner race defect was tracked as the bearing slowed. Although some of the amplitudes are slightly scattered they define a nearly linear curve over the range of speeds observed. Since the "Peak" amplitude of a periodic wave is typically proportional to its "Standard Deviation" the nominal trends of nearly all internal defects will follow similar trends as previously shown in Figure 1.

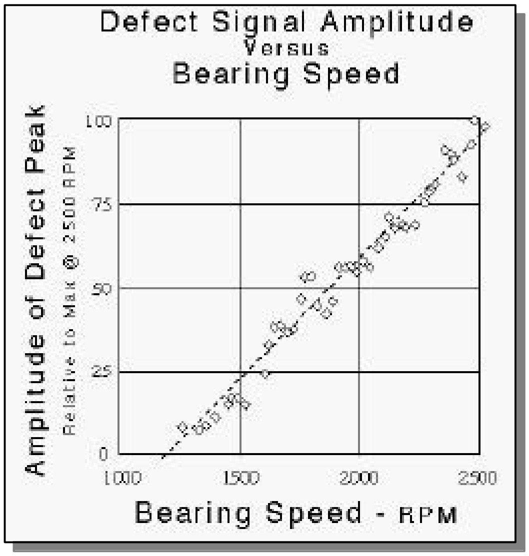

Figure 2 Bearing Defect Amplitude Vs Speed

Note also, in the example shown here that the acoustic signal emitted by the defective bearing approaches a very low level even while the bearing is rotating. This implies that a threshold speed must first be reached before a detectable audible output is emitted by a rotating bearing [Ref. 4].

IDENTIFYING DEFECTIVE BEARING SIGNATURES

Bearings that contain internal defects exhibit distinct vibration and acoustic signatures from those that have no defects. Consider the time traces shown in the next column in Figures 3-5. These acoustic signatures are taken from a "**Good Bearing**", a bearing with "**Multiple Internal Raceway Spalls**" and one that has a "**Single Outer Raceway Spall**". Each trace is plotted to the same scale and was filtered to clearly reveal its faulty nature [Ref. 3].

To illustrate how filtering can reveal hidden signal structures that are directly associated with a bearing's internal defects Figure 6 is presented. Here the filtered ,as well as the unfiltered parts of the same signature are plotted along a common time base. The higher pulsed nature of the upper trace is a direct result of the damaged internal components of the examined bearing. This can be clearly established by determining the repetition rate of the pulsed signature after filtering has been performed.

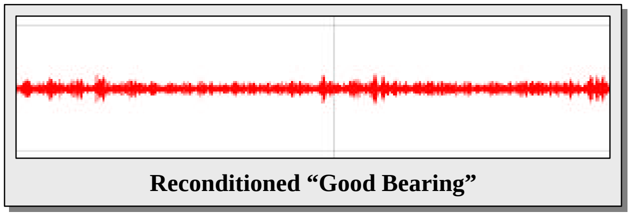

Figure 3 Sample Bearing Time Based Acoustic Signature

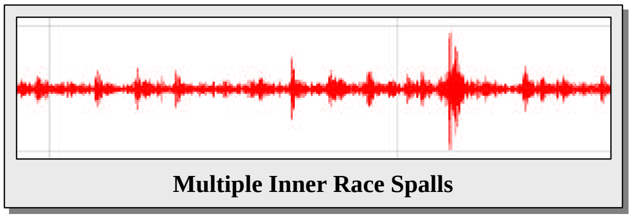

Figure 4 Sample Bearing Time Based Acoustic Signature

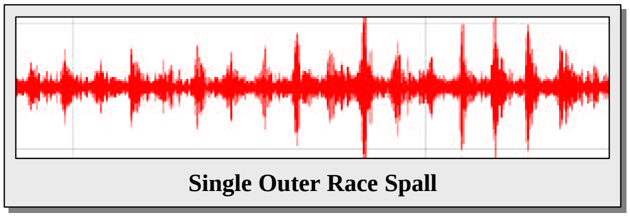

Figure 5 Sample Bearing Time Based Acoustic Signature

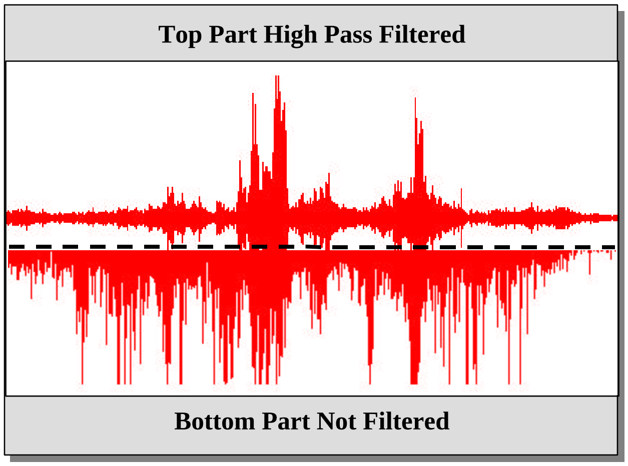

Figure 6 Two Time Based Acoustic Signatures Compared

A COMPARISON OF SOUNDS FROM BIRDS AND BEARINGS

Listening carefully to the repetitive signatures produced by some bearing defects one might be tempted to declare there's a "Woodpecker" in there somewhere. If these defect signatures are really like those made by birds found in our own backyard – what diagnostic lesson might be learned from reviewing the bird sounds we commonly hear? Just as we looked above at the most frequently occuring bearing faults, let's first consider the most common bird's vocalizations.

The latest bird sites on the internet have a wealth of information about birds. One website gives the result from a 1998 backyard survey that classified over 500,000 birds in just four days, last February. The **Great '98 Backyard Bird Count** created a full census of the backyard birds in North America. Counted by ordinary citizens at a time when migratory birds are just getting ready to head north from their winter retreats.

Table 2 provides the number and type of birds seen in the study. The study concluded that only twenty species make up over 80% of the birds found in our winter yards. There were over 100 common species found in the backyards throughout the country. Every geographic North American region is represented and a wide cross-section of birdwatcher's participated. Fourteen thousand forms were collected for analysis.

Table 2 Top 20 Birds from the 1998 Backyard Survey

Common Name	Number	%	Cum
European Starling	65951	10.54	11
House Sparrow	39767	06.35	17
Mourning Dove	39034	06.24	23
Common Grackle	38184	06.10	29
American Goldfinch	34452	05.50	35
American Crow	33661	05.38	40
House Finch	31639	05.06	45
Dark-eyed Junco	31284	05.00	50
Black-capped Chickadee	29786	04.76	55
Common Redpoll	25067	04.01	59
Red-winged Blackbird	22022	03.52	62
American Robin	21857	03.49	66
Blue Jay	17846	02.85	69
Northern Cardinal	17124	02.74	72
Pine Siskin	10853	01.73	73
Rock Dove	10824	01.73	75
Tufted Titmouse	10531	01.68	77
Brown-headed Cowbird	9388	01.50	78
Cedar Waxwing	8698	01.39	80
Downy Woodpecker	8359	01.34	81

Vocalizations from these birds are readily available. Some song files can be found on the internet and available for downloading and further examination. Cornell's Lab of Ornithology provides an extensive library on the web along with colored pictures of the birds that created the songs. Others can be found on CD's and are available in local bookstores or bird feed supply stores. The Audubon Society offers an interactive CD that contains over 700 species. Sample sounds are included on their computerized listing for many of the birds listed.

Most bird song are simple yet intricate as shown in Figure 7 (a full page of time based signals from the top 20 birds). Simple in that parts of the signatures are sometimes repeated again and again -- just as failing bearings often do. The bird song are also intricate in that many contain rapid and varying pitch changes throughout their vocalizations. This is similar to the way bearings produce side bands and/or frequency changes as defects force the internal components around within the bearing.

The true character and depth of information contained in a single bird vocalization is learned when a simple simulation is attempted. Figures 8-11 provide visual images from such an attempt. The two images in Figure 8 provides the amplitude variation found in a typical bird song. The upper trace is the real

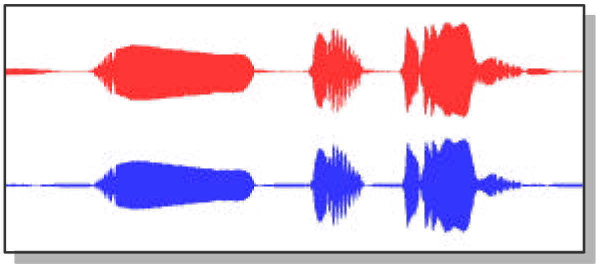

Figure 8 Simulated Bird Song – Upper Trace is Real

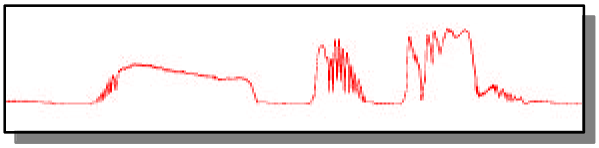

Figure 9 Envelope of the Real Bird Song Used in Simulation

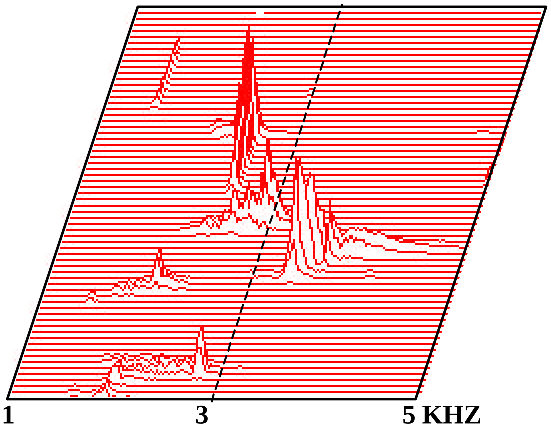

Figure 10 Waterfall Spectra from the Real Bird Song

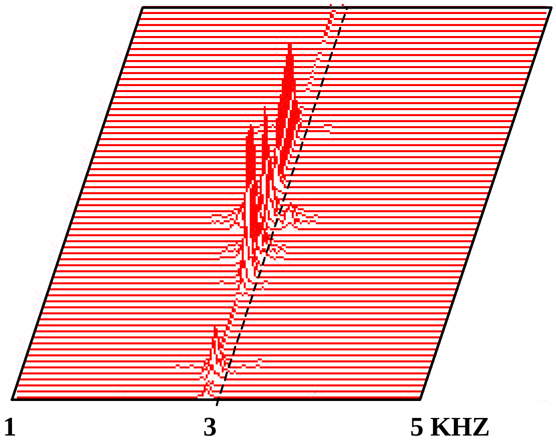

Figure 11 Waterfall Spectra from the Simulated Bird Song

vocalization and the lower trace is the simulated one. The simulated signature was produced by multiplying the **"Envelope"** of the original song by a simple sine-wave of the average frequency found in the real signature. The simulated response looks good to the "eye" and shows a near mirror-like image of the original. To the ear, however, playback of the simulated audio signal proves disappointing. Unlike the "eye" the ear (and brain) proves to be a highly discriminating analyzer as it follows the complex changes in frequency that occur during the vocalization.

To visually see the difference that the ear quickly reveals, we need to look at a full amplitude, frequency, time based plot provided by a waterfall display (see Figures 9-10). Subtle frequency based changes that cannot be discerned in the amplitude versus time display are clear in the waterfall plots. As in bearing diagnostics it is important to use the full capability of our "eyes", "ears" and "hands" in order to understand signals from machinery that's trying to "tell" us something about its own operation as it "rattles" along.

BATS AND BEARINGS

As we have seen from reviewing the signatures of birds there is much to learn from our biological counterparts when it comes to deciphering the sounds we hear everyday – may they arise from machines or not. What then can we learn about diagnostics from bats? In a nut shell, we would do well to include the following items in our basic diagnostic tool bag, as does the lowly bat.

☐ Filter In-Coming Acoustic Information
☐ Use High Frequency Discrimination
☐ Look for Harmonics in Frequency Based Spectra
☐ Look for Side-Bands in Signals from Rotating Sources
☐ Be Aware of Doppler Shifts from Some Acoustic Signals
☐ Account for Time Delays in One or More Signals
☐ Use Neural **AND** Logic to Enhance Key Information

Of the thousands of species of mammals, one quarter are bats. Unlike gliding mammals such as the flying squirrel, bats really fly. This ability, plus other characteristics, prompted scientists to put the 1,000 bat species in their own biological order: **Chiroptera**.

Although bats see fairly well, they rely on their highly developed hearing and echolocation skills to prey on their staple flying food source -- insects. The bat can emit very high frequency "sound" which is beyond our ear's detectability. Bats typically emit 30 – 100 Khz signals directly from their mouths. These ultra-sonic waves travel out at 750 mph and return back from surrounding targets to the searching bat's ears. Bats are so adapted at using ultra-sonics that they can detect and avoid a single strand of wire in total darkness. A little bat weighing less than a fraction of an ounce is able to catch and consume up to a 1,000 mosquito-sized insects in an hour. Imagine the sophistication of his diagnostic processing system!

There is evidence that the bat routinely filters the acoustic signals he handles. Highly selective tape recordings created from some of their of favorite "targets" have been used to lure and prove that bats do not always use echolocation in their nightly search for food. Photos of repeated bat approaches to tape recorders placed in solid surfaces reveal the curiosity of these biological signal-processing wonders. Likewise, we might do well in our search for defective bearings to "tune" our instruments to those bearing frequencies that are known to specifically warn us of their impending failure.

It is no secret that high frequency discrimination is a very useful way to identify defective bearings. Ever since signals could be displayed on an oscilloscope vibration technicians have been using this diagnostic approach. An approach familiar to bats for millennia. Bearings that look like they harbor a "Downy Woodpecker" or a Dark-eyed Junco" within them have been observed and removed from machinery for years with a simple oscilloscope. And this long before there were spectrum analyzers.

Two or more harmonics are commonly used by bats to identify their targets in a background filled with many noises. Some created by other bats and some generated by the insects themselves. When the second harmonic of a returning echo matches the fundamental of that signal, these two are compared by the bat with instantaneous response. Coincidence technology applied to harmonic signals is a common operation for bats. In the diagnostics of bearings this is also a useful tool. When harmonic side-bands are present there may be something special going on in the bearing under review. Special considerations through additional study of the bearings operation may reveal an undesirable internal condition.

Doppler shifts which are the "bread-and-butter" of scanning bats is not considered in most machinery applications. The author, however, is familiar with several reasons to be well informed on this topic[Refs. 11-18]. To a bat the presence of a doppler shifted return signal implies that there is a moving target out there. The precise change (shift) in frequency provides the speed of movement, whether it be the beating of wings or speed of the flying insect. Frequency shifts as small as .01% can be detected by a bat. This in a small frequency range that is only 500 Hz wide at a base frequency of 61 kilo-Hertz. An approaching train moving at 75 mph whether it has defective bearings or not provides a 10% shift in the acoustic frequencies it emits, positively relative to the source as it approaches and then negatively after it passes.

Time delays in machinery applications are not often considered. Vibration signals arriving by air, however, lag those picked up by accelerometers mounted on the machinery. One can even find time lags in surface mounted sensors if the signals are carefully inspected. Desires to follow the output of a single vibration source in phase with two or more sensors must take these small time lag differences into account. The bat again is known to have mastered the art of deciphering time delayed signals long ago.

It is known that bats use their highly accurate echolocation to calculate the distance, or should we say time, to "lunch". Its time based resolution has been established at approximately 80 millionths of a second. This allows a bat to measure continuously small changes in distance to any meal in real-time as it flies. Combined with it capability to use frequency demodulation the detection of distance to objects has been determined to be 28,000 times better than it would be if FM ranging were not employed.

The use of neural "AND" logic is also a feature of the bats diagnostic system that lets them gage distances accurately. It has been shown [Ref. 19] that when ultra-sonic outputs from the bat are "returned" at precise delay times, they can generate an amplified internal response within their brain cortex. This response which combines the output and return signals yields high amplification pairing through an imbedded biological "AND" circuit. This logic approach provides the bat with a nerve based system for tracking very small amplitude return signals with delays in the 1-18 millisecond time frame. This is the precise timing required for tracing his favorite sources of dinner. There are several bearing diagnostic systems where this "Logic AND" approach could be put to good use.

We can't leave this subject without presenting an ultra-sonic signature from at least one bat. Figure 12 contains two eight second plots of bat echolocations [Ref.20]. These plots reveal a variety of acoustic characteristics over the time, amplitude, and frequency domains. Notice that most of the output is well above the 10,000 Hz level. Although this display does not show it clearly, frequencies at multiple harmonics of a base signal are generated by some species to produce strong striated acoustics.

BELLS AND BEARINGS

The acoustics of the London "Westminster Bell" is graphically displayed in Figure 13 [Ref. 24]. The two plots provide a clear indication of how the bell's ringing decays in amplitude over a 5 second period. The sonogram (which is a top down view of a waterfall plot) provides the individual frequency response over the same period. There are several distinct fixed frequencies that provide the notable sound emitted by this famous "Big Ben" tower clock. Unlike the wide variations in the bat signature this bell maintains a constant frequency content as these sounds diminish. I wonder what time it was? Probably time to stop!

SUMMARY

Every story deserves a good ending. In starting this review it was not clear what birds, bats, bells and bearings might really have in common. This presentation has only covered the topic in a cursory fashion. If we could extend and apply all the principles discussed in the review, we might be on our way to developing a "great" diagnostic system. If we could only build the diagnostic features of a lowly bat into a package that would quickly tell us the condition of our production machinery bearings, we might all be better for it. At the present time, however, we can only wonder at the precision and capability that comes built-inside every new bird and bat. For now we will have to settle with imitating a small portion of their capability, as best we can.

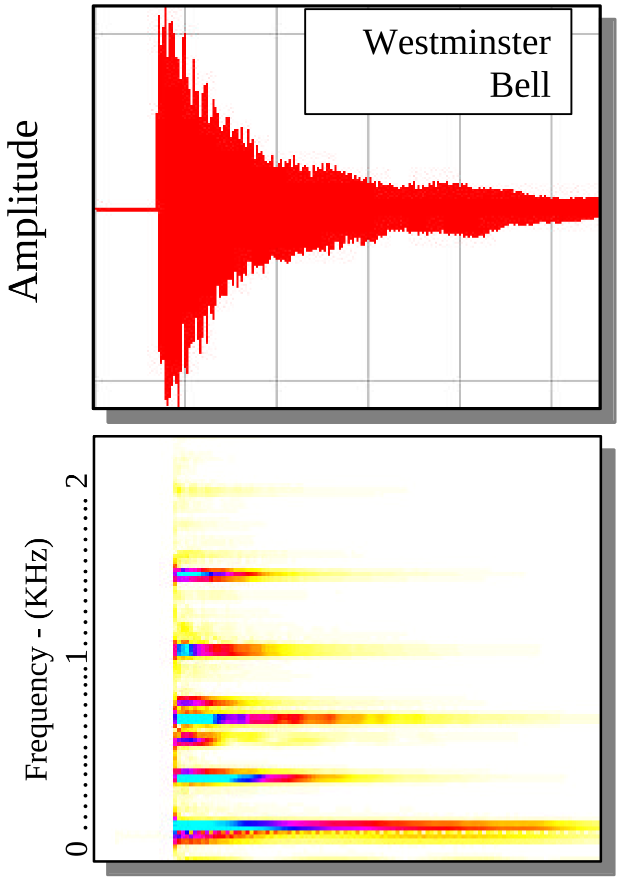

Figure 13 Clear Acoustics from the Westminster Bell

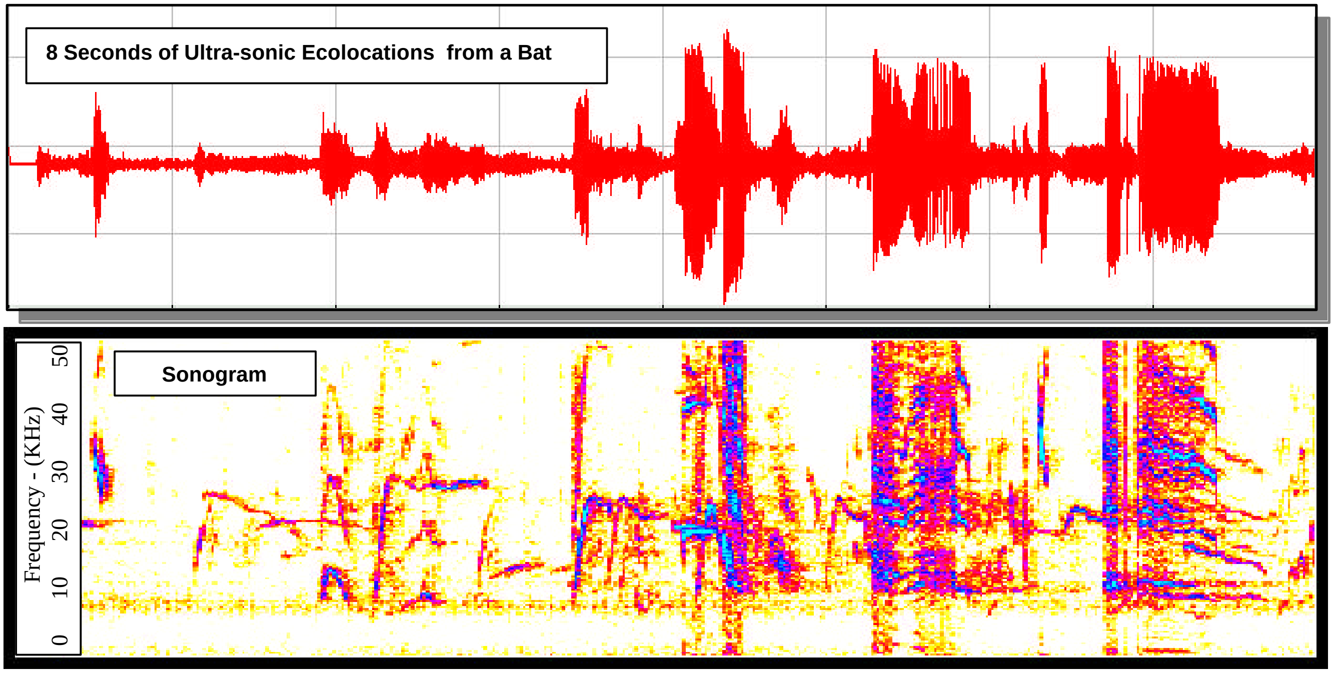

Figure 12 Ultrasonic Recording from a Bat Showing the Variation in Pitch and Amplitude of the Vocalization

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