SPECPAK:
AN INTEGRATED ACQUISITION AND ANALYSIS SYSTEM
FOR ANALYZING THE ECHOLOCATION SIGNALS OF MICROCHIROPTERA

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# TABLE of CONTENTS

## ACKNOWLEDGEMENTS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
</tr>
</tbody>
</table>

## LIST of FIGURES

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>vi</td>
</tr>
</tbody>
</table>

## ABSTRACT

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ix</td>
</tr>
</tbody>
</table>

## 1. INTRODUCTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>3</td>
</tr>
<tr>
<td>1.4</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>1.6</td>
<td>5</td>
</tr>
<tr>
<td>1.7</td>
<td>6</td>
</tr>
</tbody>
</table>

## 2. REVIEW OF SPECTRAL ESTIMATION THEORY

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>8</td>
</tr>
<tr>
<td>2.1.1</td>
<td>9</td>
</tr>
<tr>
<td>2.1.2</td>
<td>10</td>
</tr>
<tr>
<td>2.1.3</td>
<td>11</td>
</tr>
<tr>
<td>2.1.4</td>
<td>14</td>
</tr>
<tr>
<td>2.1.4.1</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>18</td>
</tr>
<tr>
<td>2.2.1</td>
<td>19</td>
</tr>
<tr>
<td>2.2.2</td>
<td>21</td>
</tr>
<tr>
<td>2.2.3</td>
<td>22</td>
</tr>
<tr>
<td>2.2.4</td>
<td>22</td>
</tr>
<tr>
<td>2.2.5</td>
<td>23</td>
</tr>
<tr>
<td>2.2.6</td>
<td>23</td>
</tr>
</tbody>
</table>
2.2.7 Kaiser Window ........................................ 24.
2.3 Conclusion ............................................. 25.

3. HARDWARE .................................................. 26.
  3.1 Hardware Specifications ............................... 26.
    3.1.1 Microphone ......................................... 27.
    3.1.2 Pre-Amplifier and Amplifier ....................... 28.
    3.1.3 Digitizing Oscilloscope ............................ 29.
    3.1.4 Desktop Computer .................................. 30.
  3.2 Conclusion ............................................. 31.

4. SOFTWARE .................................................... 33.
  4.1 Data Acquisition Subsystem ......................... 33.
  4.2 Utilities ............................................... 36.
  4.3 Signal Processing ..................................... 38.
    4.3.1 FFT - Fast Fourier Transform .................... 38.
    4.3.2 Correlogram ....................................... 39.
    4.3.3 Periodogram ....................................... 39.
    4.3.4 AR Model ........................................... 40.
  4.4 Plotting ................................................. 40.
  4.5 Software Notes ......................................... 41.
  4.6 Conclusion ............................................. 42.

5. EXPERIMENTATION & ANALYSIS ............................ 43.
  5.1 Method and Procedures ................................ 43.
  5.2 Evaluation of Estimators ............................. 44.
  5.3 Conclusion ............................................. 54.

6. CHARACTERIZATION AND IDENTIFICATION OF MICROCHIROPTERA ... 56.
  6.1 Present Characterization Methods ................... 56.
  6.2 Classification and Identification using SPECPAK ...... 58.
    6.3.1 Pteronotus parnelli............................... 60.
    6.3.2 Macrotus ........................................... 65.
**LIST of FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>General System Operation Flow</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>Periodogram Segmenting Illustration</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>System Model for AR Process</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Frequency Responses of Each Window Function</td>
<td>20</td>
</tr>
<tr>
<td>3.1</td>
<td>SPECPAK Hardware Configuration</td>
<td>27</td>
</tr>
<tr>
<td>3.2</td>
<td>Microphone Frequency Response</td>
<td>28</td>
</tr>
<tr>
<td>4.1</td>
<td>SPECPAK Menu Selection System</td>
<td>34</td>
</tr>
<tr>
<td>B.17</td>
<td>Echolocation call of Eptesicus fuscus</td>
<td>46</td>
</tr>
<tr>
<td>5.1</td>
<td>FFT - Kaiser Window</td>
<td>47</td>
</tr>
<tr>
<td>5.2</td>
<td>FFT - Rectangular Window</td>
<td>47</td>
</tr>
<tr>
<td>5.3</td>
<td>Periodogram - 4 segments</td>
<td>48</td>
</tr>
<tr>
<td>5.4</td>
<td>Periodogram - 7 segments</td>
<td>49</td>
</tr>
<tr>
<td>5.5</td>
<td>Periodogram - 20 segments</td>
<td>50</td>
</tr>
<tr>
<td>5.6</td>
<td>Correlogram - 32 lags</td>
<td>50</td>
</tr>
<tr>
<td>5.7</td>
<td>Correlogram - 64 lags</td>
<td>51</td>
</tr>
<tr>
<td>5.8</td>
<td>Correlogram - 128 lags</td>
<td>52</td>
</tr>
<tr>
<td>5.9</td>
<td>AR Estimate - order 3</td>
<td>53</td>
</tr>
<tr>
<td>5.10</td>
<td>AR Estimate - order 5</td>
<td>53</td>
</tr>
<tr>
<td>5.11</td>
<td>AR Estimate - order 10</td>
<td>53</td>
</tr>
<tr>
<td>5.12</td>
<td>AR Estimate - order 20</td>
<td>54</td>
</tr>
<tr>
<td>6.1</td>
<td>Representations of sound spectrograms</td>
<td>57</td>
</tr>
<tr>
<td>6.2</td>
<td>FFT of fig B.1</td>
<td>60</td>
</tr>
<tr>
<td>6.3</td>
<td>AR (order 10) for fig. B.1</td>
<td>61</td>
</tr>
<tr>
<td>6.4</td>
<td>FFT for figure B.2</td>
<td>62</td>
</tr>
<tr>
<td>6.5</td>
<td>AR Model (order 10) for fig. B.2</td>
<td>62</td>
</tr>
<tr>
<td>6.6</td>
<td>FFT for fig. B.4</td>
<td>63</td>
</tr>
<tr>
<td>6.7</td>
<td>10th order AR Model for figure B.4</td>
<td>63</td>
</tr>
<tr>
<td>6.8</td>
<td>FFT for figure B.7</td>
<td>64</td>
</tr>
<tr>
<td>6.9</td>
<td>10th order AR Model for figure B.7</td>
<td>64</td>
</tr>
<tr>
<td>6.10</td>
<td>13th order AR Model for figure B.7</td>
<td>65</td>
</tr>
<tr>
<td>6.11</td>
<td>FFT for figure B.8</td>
<td>66</td>
</tr>
<tr>
<td>6.12</td>
<td>10th order AR Model for figure B.8</td>
<td>66</td>
</tr>
</tbody>
</table>
Figure 6.13  FFT for figure B.11  67.
Figure 6.14  13th order AR Model for figure B.11  67.
Figure 6.15  FFT for figure B.15  68.
Figure 6.16  13th order AR Model for figure B.15  68.
Figure 6.17  FFT for figure B.16  69.
Figure 6.18  15th order AR Model for figure B.16  69.
Figure 6.19  FFT for figure B.19  71.
Figure 6.20  FFT for figure B.21  71.
Figure 6.21  10th order AR Model for figure B.21  72.
Figure 6.22  FFT for figure B.22  72.
Figure 6.23  5th order AR Model for figure B.22  73.
Figure 6.24  FFT for figure B.24  73.
Figure 6.25  FFT for figure B.28  74.
Figure 6.26  10th order AR Model for figure B.28  75.
Figure 6.27  7th order AR Model for figure B.32  76.
Figure 6.28  8th order AR Model for figure B.33  76.
Figure 6.29  8th order AR Model for figure B.34  77.
Figure 6.30  FFT for figure B.36  77.
Figure 6.31  FFT for figure B.37  78.
Figure 6.32  FFT for figure B.38  78.
Figure B.1  Pteronotus parnaellii - 1  100.
Figure B.2  Pteronotus parnaellii - 2  100.
Figure B.3  Pteronotus parnaellii - 3  100.
Figure B.4  Pteronotus parnaellii - 4  100.
Figure B.5  Pteronotus parnaellii - 5  101.
Figure B.6  Pteronotus parnaellii - 6  101.
Figure B.7  Pteronotus parnaellii - 7  101.
Figure B.8  Macrotus - 1  102.
Figure B.9  Macrotus - 2  102.
Figure B.10  Macrotus - 3  102.
Figure B.11  Macrotus - 4  102.
Figure B.12  Macrotus - 5  103.
Figure B.13  Macrotus - 6  103.
Figure B.14  Macrotus - 7  103.
Figure B.15  Macrotus - 8  103.
Figure B.16  Macrotus - 9  
Figure B.17  Eptesicus fuscus #1 - 1  
Figure B.18  Eptesicus fuscus #1 - 2  
Figure B.19  Eptesicus fuscus #1 - 3  
Figure B.20  Eptesicus fuscus #1 - 4  
Figure B.21  Eptesicus fuscus #1 - 5  
Figure B.22  Eptesicus fuscus #1 - 6  
Figure B.23  Eptesicus fuscus #1 - 7  
Figure B.24  Eptesicus fuscus #1 - 8  
Figure B.25  Eptesicus fuscus #1 - 9  
Figure B.26  Eptesicus fuscus #1 - 10  
Figure B.27  Eptesicus fuscus #1 - 11  
Figure B.28  Eptesicus fuscus #2 - 1  
Figure B.29  Eptesicus fuscus #2 - 2  
Figure B.30  Eptesicus fuscus #2 - 3  
Figure B.31  Eptesicus fuscus #2 - 4  
Figure B.32  Eptesicus fuscus #2 - 5  
Figure B.33  Eptesicus fuscus #2 - 6  
Figure B.34  Eptesicus fuscus #2 - 7  
Figure B.35  Eptesicus fuscus #2 - Communication Call  
Figure B.36  Eptesicus fuscus #3 - 1  
Figure B.37  Eptesicus fuscus #3 - 2  
Figure B.38  Eptesicus fuscus #3 - 3
ABSTRACT

A new application of digital spectrum estimation algorithms is presented. The frequency content of ultrasonic echolocation signals emitted by various bat species are investigated. Using several different analysis algorithms, an empirical determination of the most suitable technique for this class of waveform is reached. In addition, interspecies and intraspecies classification of bats utilizing the most appropriate estimators is investigated for feasibility.

The motivation for this research arose from a need in the zoological community for faster, more efficient, and more accurate analysis tools. Using computers and digital spectral estimation techniques, in conjunction with a high-speed analog-to-digital converter and broadband microphone, spectral information could be obtained and analyzed faster, and more efficiently due to the elimination of unnecessary or inappropriate processing.

Results showed that the most appropriate analysis algorithm for these waveforms was dependent on the spectral properties of the particular signal. The FFT with a Kaiser window applied was shown to be very useful, and the Autoregressive parametric estimator with an approximate system order of 8 to 10 also proved to be advantageous in certain situations. However, the conclusion is reached that accurate spectral interpretation will require analysis over several time bins in the signal, in order that frequency information with respect to time can be obtained.

The spectra produced by the estimators indicated surprisingly
distinguishable characteristics with peaks that were easily discernable. Past research findings regarding spectral shape of echolocation bursts were supported, and the implication is that classification of species or even individuals is possible. With some modification and enhancement, the system could be contained in a portable computer, allowing use in remote locations where classification is the primary intent.
1. INTRODUCTION

In the animal sciences, the problem of characterizing an animal by the digital analysis of the sound it broadcasts is mostly unexploited by present-day researchers. The problem is most applicable when it involves those animals which utilize frequencies above the audible range for their normal activities. This group of animals has the unique ability to emit and detect ultrasonic acoustic signals, and since humans do not share the ability, only a small amount of scientific attention given to the problem. Also, the fact that ultrasonic signals require much faster equipment to accurately convert from the natural analog state to a digital form conducive to machine manipulation makes the problem of characterizing this group of animals by their acoustic properties even more difficult.

This work presents the development of a spectral analysis system for ultrasonic signals, utilizing modern digital signal processing methods, which allows the investigator to accomplish the spectral estimation task effectively, and with a higher degree of accuracy than has previously been achieved. The process involves translating the digitized time data via frequency domain transforms and utilizing this information intelligently in the characterization of bat species. Some significant discoveries are presented which were revealed through the use of these digital spectral estimation methods.

1.1 Evaluation of Relevant Present and Past Work
Albeit commonplace in the engineering field, the application of digital signal processing methods in the animal sciences has not been widely realized. Presently, most signal analysis of ultrasonic waveforms is accomplished in one of two ways. One method is to use high-speed magnetic recordings and play back the signal at a slower speed to bring the frequencies in the audible range. This results in a base-banding operation which corrupts the original signal by introducing a sinusoidal modulation. Dealing with this issue requires taking the modulation into account in the spectral analysis. The whole procedure yields fairly accurate results but with a great deal more effort than is necessary.

The other procedure for ultrasonic signal analysis is to input the signal directly into a spectrum analyzer which uses a standard Fast Fourier Transform algorithm and which may or may not have a window function available. This method has its own faults as can be seen in chapter 4. There are commercial software packages and data acquisition systems which attempt to meet the needs of one area or the other, but no one package addresses the demands of this ultrasonic application. It is therefore necessary to design a system which will satisfy the above requirements.

1.2 System Overview

The goal of this work is to develop a system that will give the scientist a more efficient and accurate tool for ultrasonic signal analysis, and to use this system to identify several species of bats
based on the frequency properties of their acoustic emission. The system designed consists of a high-frequency microphone attached to an amplifier, a very high speed digitizing oscilloscope, an IBM compatible desk-top computer, and specially designed software. The menu-driven software processes the digitized signal with one of four different user specified algorithms to produce a frequency domain representation of the signal. The software includes graphing capabilities so visual results are readily available.

The spectral analysis algorithms include the Fast Fourier Transform, Correlogram, Welch Periodogram, and an autoregressive parametric modeling technique. In addition, five different time domain window functions are included for optional application to the discrete-time signal. The Bartlett, Blackman, Hamming, Hann, and Kaiser family of windows are available as well as the default rectangular window.

1.3 Fundamental System Operation

As shown by the block diagram in Figure 1.1, the system operation is very straightforward. First a signal is located and the microphone directed to capture the analog waveform. Then the signal is passed through a converter to produce a digital version of the signal. This data sequence is then used in the software to analyze the frequency content with any or all of the available methods, and graphic visual aids generated. The end result is output that can be used intelligently in the characterization or identification of animal species or even specific individuals.
1.4 Digital Signal Processing Overview

Four spectral estimation techniques are incorporated in the software. One of the methods, which is classically implemented for this type of analysis is the Fast Fourier Transform. This algorithm uses a deterministic approach to the time-domain signal, since it assumes that the signal can be represented in some closed form, usually as a combination of sinusoids with varying amplitudes and frequencies. This is the normally implemented solution to the classic harmonic analysis problem. The other three methods included are the Correlogram, Periodogram, and a parametric Autoregressive (AR) approach using the Burg technique for parameter estimation. These three methods capitalize on statistical properties of a "random" signal to evaluate the frequencies
present. The estimation methods, along with various window functions, make up a very useful digital signal processing toolbox for spectral estimation.

1.5 Application Illustration

One example of the use of the system is animal identification in remote areas; specifically, to identify, in real time, what species of bats are present based on the comparison of the spectral information given by SPECPAK and the collection of information already attained. A large amount of data on the spectral content of a particular animal species or even an individual animal would be collected. The scientist could then use this information as a reference for new data comparison. In this way, accurate identification could be accomplished in the same way that fingerprints serve to identify humans.

1.6 Project Evaluation

A successful project is one which gives timely information serving either to better understand the physical properties of the signal by seeing clearly the frequency domain representation, or to accurately characterize a particular species based on the spectral content of the acoustic echolocation signals emitted. The work presented accomplishes this goal. This sort of application has many variations which should significantly advance animal ultrasonic communication research; yielding a clearer understanding of communication, echolocation, hunting, and
defense activities in animals which utilize ultrasonic frequencies.

1.7 Thesis Format

Much effort was expended on this manuscript in providing an organized format for the reader. Chapter 1 is the introduction which familiarizes the reader with the basic ideas presented in the rest of the paper. The intention is that the reader get a firm grasp on the ultimate goals of the project, the building blocks required, and the issues that were dealt with.

Chapter 2 is devoted to the theory of the digital signal processing methods utilized. A detailed examination of the theoretical spectral performance is presented and supported by plots. The six windowing algorithms implemented in the analysis package are presented and the issues requiring them are discussed.

Chapter 3 presents a discussion of the hardware necessary for completion of the prototype system. This includes all information on the hardware operation as a whole, as well as detailed discussion of each component and its required contribution. Some theoretical relations are presented here to more naturally support the text. The issue of portability is addressed in the context of the ideal analysis system.

Chapter 4 contains all pertinent material regarding the software aspects of the project. Since the objective is to explain how the software is used, this chapter follows more of a narrative format. Each SPECPAK menu module is discussed in detail and all sub-choices are
addressed.

Chapter 5 describes the experimental procedure used for data acquisition and analysis. All the signals in appendix B were obtained through this procedure. The performance of each spectral estimator is then evaluated as applied to one echolocation call, and some conclusions as to the most appropriate estimation algorithm are reached.

Chapter 6 is concerned with the application of the appropriate spectral estimation methods to actual ultrasonic echolocation calls of several Microchiroptera. The discussion, supported by plots, examines the results of the spectral estimates as applied to the acquired signals illustrated in appendix B.

Chapter 7 presents a discussion of the conclusions drawn from the research, development, and experimentation of SPECPAK; the primary focus being the employment of the system as it was intended, and the successes and failures of its application. This chapter attempts to address and resolve the issues faced during the research process. There is also a discussion of future enhancements to the SPECPAK system that would significantly improve performance and applicability.
2. REVIEW OF SPECTRAL ESTIMATION THEORY

Analysis of a given signal of interest usually starts with some assumption about the characteristics of the signal, e.g. narrowband, wideband, noisy, among others. For the purposes of this thesis however, no assumptions are made regarding the signal. The spectral estimation methods applied give reasonable insight into the signal construction and therefore presuppose any conjecture. The analysis is straight-forward with the procedures for implementing the estimators being derived from existing algorithms and the estimator test output compared with proven data from Marple[1].

2.1 An Overview of Spectral Estimation Procedures

The concept of harmonic analysis or characterization of the frequency content of a signal has been studied for several centuries, but it was not until the advent of the digital computer that actual implementation of the algorithms produced by the theory was possible for any practical data. The reason being that spectral estimation is a very numerically intensive craft, with a 1024 point Discrete Fourier Transform requiring more than one million multiplication operations. This computational cost was prohibitively time consuming. Today, however, the implementation of 16,384 point and greater FFT’s are commonplace and so the analysis of very long data records is now a practicality.

Four spectral estimation methods were chosen to include in the
analysis software. Three of the methods, the FFT, the Correlogram, and the Welch Periodogram, all have very similar mathematical properties, based on the Discrete Fourier Transform. The autoregressive modeling technique is the fourth estimator implemented in the software and its performance is shown to be drastically different from the other three. Since it is not based on the Discrete Fourier Transform but rather on an approach employing systems and filter theory, it is considered a "Parametric" estimator.

2.1.1 Windowed Fast Fourier Transform

Given an N point sequence, $x[n]$, representing N samples of an analog time domain signal, the Discrete Fourier Transform for relating this signal to its discrete frequency domain representation, $X[k]$, is

$$X[k] = \sum_{n=0}^{N-1} w[n] x[n] e^{-j\frac{2\pi kn}{N}}$$

(2.1)

where $k$ is the frequency bin index and $w[n]$ is the window function applied to the data set. This procedure is a very inefficient and time consuming, even with today's computing resources. However, an algorithm called the Fast Fourier Transform (FFT), was developed in 1965 by Cooley and Tukey, which optimized the implementation of (2.1) such that the computational requirements were reduced by an order of $N$. This algorithm forms the basis for many modern digital signal processing methods, especially those concerned with spectral estimation.

When applied with an appropriate window function, the FFT estimator is very useful for gaining a "first order feel" for the
frequency content of a given signal. In many cases, this is all that is necessary for successful characterization of a bat's echolocation call.

2.1.2 Correlogram Estimator

In the previous section, the direct transformation of the data was used in forming a spectral estimate, but this method, however useful, is not strictly a power spectral density (PSD) estimate. The PSD function can be defined as the discrete-time Fourier transform of the true autocorrelation sequence for the data [1,ch.4].

Power Spectral Density approximations which depend on correlation estimates from the data are collectively called correlogram methods of spectral estimation [1,p.130]. The general form for the Correlogram PSD estimator is

\[ P_c(f) = T_s \sum_{m=-L}^{L} w[m] r_{xx}[m] e^{-j2\pi fmT_s} \]  

(2.2)

which can be shown to be the Discrete Fourier Transform (2.1) of the sequence obtained by multiplying an unbiased 2L+1 lag autocorrelation sequence estimate by a window function. The lag index \( m \) is used instead of \( n \) for consistency with the nomenclature. This autocorrelation sequence estimate, \( r_{xx}[m] \), is given by
Using the conjugate symmetry property of the autocorrelation,

\[ r_{xx}[m] = r_{xx}^*[-m] \]  

(2.4)

the estimates for the negative lags can easily be computed [1,p.147].

The Correlogram can readily be seen to have a statistical derivation since the autocorrelation (a statistical measure) is used in the definition. This gives rise to the interest in the expected value of the estimator, \( P_c(f) \), which can be shown to be

\[ E[P_c(f)] = P_{xx}(f) \ast \Omega(f) \]  

(2.5)

where \( P_{xx}(f) \) is the true power spectral density function of the data, and \( \Omega(f) \) is the spectral function of the window sequence. The resulting spectral estimate is therefore a convolution of the true PSD with the DFT of the window function.

It is difficult to categorize the advantages and disadvantages of the Correlogram PSD estimate because the performance is so signal dependent. In some cases the estimator will produce very accurate spectra and in other cases the estimate variance is intolerable.

Chapter five will reveal the performance of the Correlogram on the signals of interest in this work.

2.1.3 Welch Periodogram Estimator
The other classical spectral estimation algorithm is the Welch Periodogram. A periodogram is any PSD estimator that combines direct transformation of the data with some sort of ensemble averaging is called a periodogram estimate. This estimator performs FFT's on subsets of the total data sequence and averages the transforms to get a more statistically reliable estimate of the power spectral density. Actually, the above system was presented by Bartlett [1,p.153], and Welch modified the approach to include windowing of the data segments and segment overlapping. The effect is to decrease the estimate variance by increasing the number of segments available for transformation in the finite data record.

The process of computing the Welch Periodogram, as taken from

\[
\text{Number of Segments} = \frac{N - D}{D - S} + 1
\]

Figure 2.1 Periodogram Segmenting Illustration

[1,p.155] is very intuitive. Assuming an N-point data set, \( x[0] \) ... \( x[N-1] \), divide the set into \( P \) segments of \( D \) points each, and overlap the
segments by $S$ points. The total number of segments in the record is then given as the integer part of $(N-D)/(D-S)+1$. (see Figure 2.1)

The Welch spectral estimate is given by (2.6)

$$P_w(f) = \frac{1}{P} \sum_{p=0}^{P-1} \hat{S}_{xx}^{(p)}(f)$$

(2.6)

where the estimate of the weighted $p$th segment $x^{(p)}[n] = w[n]x[n+p(D-S)]$ for $0 \leq n \leq D-1$ is

$$\hat{S}_{xx}(f) = \frac{1}{UDT} |X^{(p)}(f)|^2$$

(2.7)

The term $X^{(p)}(f)$ is the Discrete Fourier Transform of the $p$th segment

$$X^{(p)}(f) = T_s \sum_{n=0}^{D-1} x^{(p)}[n] e^{-j2\pi fnT_s}$$

(2.8)

and $U$ is the energy of the data window

$$U = T_s \sum_{n=0}^{D-1} w^2[n]$$

(2.9)

The Periodogram also has a statistical derivation due to the ensemble averaging over the segment transforms. So again we are interested in the expected value of the estimator, $P_w(f)$, which can be shown to be

$$E[P_w(f)] = P_{xx}(f) \ast \frac{1}{U}|W(f)|^2$$

(2.10)

The resulting spectral estimate is therefore the convolution of the true PSD with the magnitude of the DFT of the window sequence squared and scaled by the window energy.
Similar to the Correlogram method, the Periodogram estimator is difficult to evaluate without application to the signal of interest, but a detailed examination of the method is presented in chapter five.

2.1.4 Autoregressive (AR) Modeling Estimator

In deciding on appropriate spectral estimation methods for a given signal, the issue of frequency resolution is a factor. In order to have the flexibility of analyzing the signal under a broad range of assumptions, the availability of at least one high resolution spectral estimation algorithm is necessary. The parametric estimation method based on autoregressive modeling of the data is therefore included. The development of the theory behind this algorithm follows.

A p-th order AR process is generated using the system model shown in Figure 2.2. The input to the p-pole filter is a zero mean white

![Figure 2.2 System Model for AR Process](image-url)
noise sequence \( w(n) \) with variance \( \sigma_w^2 \).

The system has a difference equation representation

\[
\chi(n) = - \sum_{k=1}^{p} a_k \chi(n-k) + w(n)
\]  \hspace{1cm} (2.11)

where the \( a_k \)'s are the delay line gains shown in Figure 2.2. Using linear systems techniques, the z-transform of this filter evaluated on the unit circle reveals the power spectrum of the process,

\[
P_x(f) = \frac{\sigma_w^2}{\left| 1 + \sum_{k=1}^{p} a_k e^{-j2\pi fk} \right|^2}
\]  \hspace{1cm} (2.12)

There exists a \( p \)-th order all-zero filter, \( A_p(z) \) that will recover \( w(n) \) from \( x(n) \). This filter is called the inverse filter of the AR process and is obtained by the application of a forward linear prediction algorithm [1, ch. 7] to the data sequence. Removing any predictable components from \( x(n) \) yields the forward prediction error sequence \( e_p(n) \), which is equivalently, \( w(n) \). Since the signal of interest has been assumed to be generated by a \( p \)-th order AR process, the spectral estimation problem is now that of estimating the \( p \)-th order linear prediction coefficients, and the power (variance) of the prediction error sequence.

The AR power spectral density expression can be shown to have the equivalent representation of (2.13) [1, pg. 183],

\[
P_x(f) = \frac{T \rho_w}{|A(f)|^2} = T \sum_{k=-\infty}^{\infty} r_{xx}[k] e^{-j2\pi fkT}
\]  \hspace{1cm} (2.13)

which is identical to the Correlogram PSD for an infinite number of
lags. Hence the very sharp peaks in the spectral estimates produced by this method.

This is the most promising (see ch. 7) estimator for the type of analysis presented in this work. The high resolution properties are very appropriate in this particular application since detailed spectral information is necessary for accurate identification of species. By simply incorporating into the estimation problem some assumptions about how the data were generated (that the data is from a p-th order autoregressive process), surprising results can be obtained [3, pgs. 596-646] (see also chapters 5 and 6).

2.1.4.1 Burg's Algorithm for AR Parameter Estimation

There are several algorithms in the literature for calculating the AR parameters, one of which is known as Burg's algorithm, or the "harmonic algorithm" [1, ch. 8]. Introduced in 1967 by John Burg, and expounded upon by several authors in later years [1][21][24], the method has been classified as a "maximum entropy" method. This type of numerical procedure is described in [21]. However, the Harmonic algorithm for estimating AR parameters should not be confused with Burg's original concept of maximum entropy spectral analysis.
The idea behind Burg's parameter estimation algorithm is to minimize the arithmetic mean of the forward and backward linear prediction error powers,

\[
\rho_{rb}^p = \frac{1}{2N} \sum_{n=p+1}^{N} |e_p^f[n]|^2 + |e_p^b[n]|^2 \tag{2.14}
\]

A discussion of linear prediction theory is omitted here (refer to [23] for a detailed development), but the recursive relationships that result for the forward and backward prediction errors, \(e_p^f[n]\) and \(e_p^b[n]\), are shown in eq. 2.15 for clarity.

\[
e_p^f[n] = e_{p-1}^f[n] + \kappa_p e_{p-1}^b[n-1] \\
e_p^b[n] = e_{p-1}^b[n-1] + \kappa_p^* e_{p-1}^f[n] \tag{2.15}
\]

The estimate for the reflection coefficient term, \(\kappa_p\), in (2.15) is found by setting the complex derivative of (2.14) with respect to \(\kappa_p\) equal to zero and solving. This yields the following,

\[
\kappa_p = \frac{-2 \sum_{n=p+1}^{N} e_p^f[n] e_p^b[n-1]}{\sum_{n=p+1}^{N} (|e_p^f[n]|^2 + |e_p^b[n-1]|^2)} \tag{2.16}
\]

This reflection coefficient estimate represents the harmonic mean between the forward and backward partial correlation coefficients. A recursion discovered by Andersen [24] which simplifies evaluation of the denominator in (2.16) is given by (2.17),

\[
DEN_p = (1 - |\kappa_{p-1}|^2) DEN_{p-1} - |e_{p-1}^f[p]|^2 - |e_{p-1}^b[N]|^2 . \tag{2.17}
\]
where $\text{DEN}_p$ is the denominator expression in (2.16).

This is the algorithm implemented in the SPECPAK software for the autoregressive model power spectral density estimator. The code was translated from Marple's original FORTRAN routine as listed in [1].

2.2 Window Basics and Windowing Functions

The spectral estimation techniques presented above would, for the most part, be ineffective mathematical theories without the application of data windowing. The AR Model is an exception to this since no windowing is involved, but the importance of window functions in effective spectral estimation cannot be overstated. Since the continuous version of the transform in (2.1) has limits of $-\infty$ to $+\infty$, the time sequence is assumed to have infinite duration. The limits on the sum from $n=0$ to $N-1$ imply that only a portion of the infinite time signal is used. Actually the DFT is using an implied rectangular window function (2.18) to cut off the data at $n = 0$ and $n = N-1$. The result is a finite $N$-point sequence which is then transformed via eq. 2.1. From a frequency domain perspective, this implied window has a very significant implication.

It is because of this implication in sampling infinite length signals that the theory of data windows has been developed. Since the truncation is a necessary process (infinite sequences are not practical), the next best thing is to design the window such that the spectral properties are exploited.
2.2.1 Window Frequency Response

Looking at the frequency domain representations of the windows reveals the problem more readily. Figure 2.3 shows the frequency response of each window implemented in the SPECPAK software, normalized to 0 dB on the y-axis and \(-Fs/2\) to \(Fs/2\) on the x-axis, where \(Fs\) is the sampling frequency. The large peak in the middle of each plot is called the 'Main Lobe', and the peaks on either side are called the 'Side Lobes'. The width of the main lobe and the relative height of the side lobes are important parameters in spectral analysis. They determine how much resolution can be obtained in the spectral estimate, and how much error is introduced from the implicit truncation of the data. Recall that the implicit convolution operation in spectral estimates of finite data, and the error introduced in the estimate is directly related to the spectrum of the "truncating" sequence or "window". If the main lobe of this window spectrum is very narrow, then better resolution is expected, but a narrow main lobe usually means higher side lobes, which also cause errors in the spectral estimate. This tradeoff between main lobe width and peak side lobe level is the primary concern of window design.

The spectra produced from estimators using the DFT algorithm (or the more efficient FFT algorithm) are biased because multiplication in the time domain manifests itself in the frequency domain as a convolution. In the case of (2.1), the rectangular window frequency response, shown in Figure 2.3.a, is convolved with the true spectra of the signal. Therefore what is seen in the spectral estimate using the simple
Figure 2.3 Frequency Responses of Each Window Function in SPECPAK
transform as shown in (2.1) can be a very bad representation of the actual frequency content because of the "smearing" effect of the convolution.

For the SPECPAK program, six different windows are available for application to the estimator; they are the naturally occurring Rectangular (No window) Window, the Triangular (Bartlett) Window, and the Blackman, Hamming, Hanning, and Kaiser-Bessel windows. The following is a brief description of each window function and its spectral properties.

2.2.2 Rectangular Window

The rectangular window function is given by (2.18),

\[ w_n(n) = \begin{cases} 1 & 0 \leq n \leq N-1 \\ 0 & \text{else} \end{cases} \quad (2.18) \]

with a corresponding spectral function (2.19) [2,p.446].

\[ W(f) = e^{-j2\pi f(N-1)/2} \frac{\sin[2\pi fT_s N/2]}{\sin(2\pi fT_s/2)} \quad (2.19) \]

This Dirichlet Kernel, as it is commonly termed, has a very narrow main lobe centered about the zero frequency and a peak sidelobe level of -13 Db relative as can be seen in Figure 2.3.a. This high sidelobe level makes it a very poor window function, even though the main lobe is the narrowest of all the windows.
2.2.3 Triangular Window

The triangular window function is given by

\[ w_{\text{t}}[n] = \begin{cases} \frac{2n}{N} & 0 \leq n \leq N/2 \\ \frac{N}{2} - \frac{2n}{N} & N/2 < n < N \\ 0 & \text{else} \end{cases} \]  \hspace{1cm} (2.20)

with a corresponding spectral function \[ W_{\text{t}}(f) = \frac{2}{N} e^{-j\pi f \left( \frac{N}{2} - 1 \right)} \left[ \frac{\sin(\pi f \left( \frac{N}{2} - 1 \right))}{\sin(\pi f T_s)} \right]^2 \] \hspace{1cm} (2.21)

This function, shown graphically as Figure 2.3.b, is the square of the Dirichlet Kernel [4,p.59]. The frequency response has a main lobe width twice that of the rectangular window, but the peak side lobes are down to -25 dB relative. One would not expect a significant performance improvement with this window function.

2.2.4 Hamming Window

The Hamming window is given by \( (2.22) \)

\[ w_{\text{h}}(n) = \begin{cases} .54 - .46 \cos \left( \frac{2\pi n}{N} \right) & 0 \leq n \leq N-1 \\ 0 & \text{else} \end{cases} \]  \hspace{1cm} (2.22)

with a corresponding spectral function (2.23) [3,p.206], which is a combination of weighted Dirichlet Kernels.

Figure 2.3.d. is the plot of the spectral function. The main lobe width is equal to the Triangle window but the peak sidelobe level is down to -41 dB relative. This improvement makes it a good performer in
2.2.5 Hanning Window

The Hanning window is very similar to the Hamming window function where the coefficients in the definition are changed to .5 and .5. It is interesting to note that the Hamming window is a modification of the Hanning window for improved sidelobe level.

The corresponding frequency domain representation, plotted in Figure 2.3.e, is also similar with the coefficients changed from .54, .46 and .46 to .50, .25, and .25 respectively. This makes logical sense because the only change in the window function is the weighting of the cosine terms. The decay rate of the sidelobes is the trade-off for the poorer sidelobe level. The Hanning window sidelobes decay at -18 db/octave where the Hamming window sidelobes fall off at one third that rate. This gives the Hanning window the advantage of less spectral smearing.

2.2.6 Blackman Window

\[
W_h(f) = .54 \frac{\sin \left( \frac{2\pi f T_s}{2} \right)}{\sin \left( \frac{2\pi f T_s}{2} \right)} + .46 \frac{\sin \left( \frac{2\pi f T_s - \pi}{N-1} \right)}{\sin \left( \frac{2\pi f T_s - \pi}{N-1} \right)} + .46 \frac{\sin \left( \frac{2\pi f T_s + \pi}{N-1} \right)}{\sin \left( \frac{2\pi f T_s + \pi}{N-1} \right)}
\]

(2.23)
The Blackman window is given by
\[
w_b(n) = \begin{cases} 
0.42 - 0.5\cos\left[\frac{2\pi}{N}n\right] + 0.08\cos\left[\frac{2\pi}{2}n\right] & 0 \leq n \leq N-1 \\
0 & \text{else} 
\end{cases}
\] (2.24)

The frequency domain representation of this function is a summation of Dirichlet kernels very similar to (2.23) and is shown graphically in Figure 2.3.c. Due to the low sidelobe levels, this window has proven to be very valuable in the appropriate weighting of transform sequences in the narrowband ultrasonic application presented.

2.2.7 Kaiser Window

The Kaiser window function is given by
\[
w_k[n] = \frac{I_0(\pi\alpha \sqrt{1 - \left[\frac{n-N^{-1}}{2}\right]^2})}{I_0(\pi\alpha)} \quad 0 \leq n \leq N-1
\] (2.25)

with an approximate transform of (2.26).
\[
w_k(f) = \frac{N}{I_0(\pi\alpha)} \frac{\sinh\left[\frac{\alpha^2\pi^2 - \left(\frac{2\pi f N}{N}\right)^2}{2}\right]}{\sqrt{\alpha^2\pi^2 - \left(\frac{2\pi f N}{N}\right)^2}}
\] (2.26)

The parameter \(\alpha\) is an adjustable value that determines the "Time-Bandwidth" product of the window [1], and a value of \(-2.5\) has been empirically determined to give the best performance for narrowband spectral analysis situations. The frequency response, shown in Figure
2.3.f, is very similar to the Blackman window response, except for a slightly narrower main lobe (interestingly, it is wider than any of the other windows).

2.3 Conclusion

Algorithms for estimating the frequency content of a signal sequence vary with respect to performance and characteristics. Each algorithm presented produces a distinctive spectral estimate which may or may not represent the frequency information correctly. If the underlying theory behind the estimator is understood, application of the algorithm can be executed more intelligently. The windowing functions can be applied with better understanding as well.

In the SPECPAK software, much effort is expended in simplifying the utilization of these estimators. It also simplifies the acquisition process by interfacing the hardware with the computer. However, if the tools available in the program are not used intelligently, the results can be completely erroneous.
3. HARDWARE

The following chapter presents the hardware portion of the SPECPAK project. In addition to the typical specifications for data acquisition and analysis systems, such as minimum sampling rate, analog-to-digital conversion resolution, and acquisition duration, certain specifications are directly related to the ultrasonic acoustic application. They include the frequency response of the microphone, signal amplification, display resolution, and numerical processing speed, to mention a few. These issues are very important aspects in the total hardware configuration.

3.1 Hardware Specifications

The SPECPAK system hardware configuration, as shown in Figure 3.1, includes: a high-end microphone and preamplifier manufactured by Brüel and Kjær, a model 2608 Brüel & Kjær chassis-mount amplifier, a Hewlett-Packard 54201A/D digitizing oscilloscope, and an IBM-compatible personal computer running under MS-DOS. The microphone, designed for ultrasonic applications, insures accurate representation of the signal over the frequency range of interest in this work. It also requires a preamplifier for signal conditioning. The 2608 amplifier gives the user flexible gain control over the signal amplitude and the digitizing oscilloscope allows for adequate signal sampling (maximum 400,000 kHz sampling rate). An IBM compatible microcomputer runs the software and interfaces with the oscilloscope over the HPIB. Each of these
components are discussed individually in the following sections.

3.1.1 Microphone

This first phase in the overall system operation is very important since the integrity of the acquired signal depends on the accuracy of the sound pressure to electric voltage conversion. The microphone is a 1/4" Brüel & Kjær transducer unit and has an extremely flat frequency response from 10 kHz to 100 kHz (see Figure 3.1, top curve). One major drawback to this particular microphone is the cost; starting at over
$2000 for the transducer and preamplifier unit.

3.1.2 Pre-Amplifier and Amplifier

The signal, once converted to electrical voltages must be amplified to well above the ambient noise level so that a trigger condition can be detectable by the scope. The microphone comes with a pre-amplifier attached, which filters the signal, and provides a selectable gain of 0 or 20 dB. Since the amplitude range for echolocation signals differs between species, another amplifier unit is used to provide more flexible gain control. This unit, model #2608, is also manufactured by Brüel & Kjær and provides for input and output gain.
control in 10 dB increments as well as a fine gain control for smaller continuous adjustments. The preamplifier from the microphone attaches directly to the main amplifier unit through an adapter provided with the microphone assembly. The proper settings for this unit based on this application are listed below:

<table>
<thead>
<tr>
<th>Input:</th>
<th>Pre-amp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters:</td>
<td>Linear (0-200000)</td>
</tr>
<tr>
<td>Meter Function:</td>
<td>either</td>
</tr>
<tr>
<td>Input Section Attn:</td>
<td>+90 dB</td>
</tr>
<tr>
<td>Output Section Attn:</td>
<td>-30 dB</td>
</tr>
</tbody>
</table>

The last two settings are gain control values and can be adjusted in conjunction with the fine gain control for optimum performance. The oscilloscope provides amplitude scaling, but only for displaying the digitized data.

3.1.3 Digitizing Oscilloscope

An Hewlett Packard digitizing oscilloscope, model 54201A/D, was chosen for analog-to-digital conversion since it incorporated the sampling frequencies necessary for accuracy. The Hewlett Packard Interface Bus (HPIB) with IEEE-488 standard format was chosen as an interface between the scope and the desktop computer. The oscilloscope provides for sampling rates as fast as 400 MHz if desired, and can transfer the data over the HPIB by software commands. One major disadvantage to this component is the 2000 point limitation on digitized sequences. Consequently, the maximum signal duration decreases for increasing sampling frequencies. This has proven to be a very restrictive factor in the present research (see chapters 4 and 5). For
a sampling frequency of 250 kHz, the maximum duration before truncation of the signal is 9 ms. A typical echolocation call from the species *Pteronotus parnellii* will last from 10 to 20 ms.

Another less desirable way to accomplish the A/D conversion is through the installation of a PC add-in card which interfaces directly to the motherboard bus and allows for sampling of analog signals. The data can be transferred directly to a RAM disk or memory on the computer, and then converted to a format readable by the SPECPAK program. This process proved to be very slow and error-prone, with a maximum sampling rate of 100 kHz.

### 3.1.4 Desktop Computer

The computing hardware was determined by speed and display requirements for the final operation. The IBM compatible platform was chosen due to the standard use of this environment in the engineering community as well as the availability of suitable code compilers.

Even though the SPECPAK software can run on a variety of machines in the IBM PC family, it is recommended that the computer have an 80286 or higher microprocessor with a corresponding 8087 family numerical coprocessor. The numerical calculation requirements for the estimation routines in the software are very intensive and can take a great deal of time without the appropriate hardware.

Very little testing has been done to determine the suitability of the software on IBM clones, but the experimentation was performed on two different machines: an IBM Model 30/286 and an IBM Model 70/386, both
with VGA (Video Graphics Array) displays. The software requires either an EGA or VGA video system to run properly as the other video modes currently available do not produce adequate resolution for spectral plots.

3.2 Conclusion

It is a requirement that each component in the system meet certain standards for acceptable system operation. This criteria forms the basis for arriving at the system specifications described above. Since the focus of the project is to apply digital signal processing methods of spectral estimation to the signals of echolocating bats (Microchiroptera), it was decided that the system should be able to adequately evaluate any species presently known. This specification requires very high standards from all the hardware components, as well as software. For instance, the *Pteronotus parnellii* is known to produce signals with frequencies above 100 kHz, and which last for up to 30 ms. If the entire data record from a *Pteronotus* [20,pg.206] is to be sampled and the spectrum computed, the microphone must have flat frequency response into the hundreds of kHz in order to accurately transfer the signal. In addition, the high frequencies produced by this bat require a sampling rate of at least 400 to 500 kHz, and the lengthy duration requires storage of twelve to fifteen thousand points in the acquisition system. This also compels the software to have the capabilities for evaluating data sequences of this length. These specifications could not be met presently due to budget, time, and material constraints, so a
more realistic system was devised. The system presented lays the groundwork for the more elaborate and functional system of the future.
4. SOFTWARE

A menu-driven software package implementing the digital signal processing algorithms presented in chapter two and providing an automated interface to the hardware described in chapter three was developed. SPECPAK combines all the individual signal processing algorithms into a single program allowing easy access to any function. In this way, analysis of a given echolocation signal (or any other data) can be carried out in a logical sequence.

All the functions implemented in the software originate from a single main menu. From it, data acquisition, file utilities, signal processing, and plotting can be selected in any order. Depending on the action selected, other menus or input forms appear requesting more information necessary for carrying out the task. Typically, analysis of a given signal follows the order: acquisition or retrieval, signal processing, plotting, and saving. The entire menu system is shown in figure 4.1.

4.1 Data Acquisition Subsystem

The functions implementing the acquisition subsystem are specific to the Hewlett-Packard 54201A/D Digitizing Oscilloscope and are defined in the library accompanying the HP-IB programming reference. In order to successfully digitize an echolocation call, the scope parameters must be set and controlled correctly. There are three ways in which the scope parameters are set. The acquisition subroutines in the software
The SPECPAK System

MAIN MENU

- Acquisition
- Utilities
- Sig. Proc.
- Plotting
- Enter
- Samp. Freq.

Save
Retrieve
Set Directory
DOS Shell

Time
Spectrum
Window

FFT
- Seg/Ovr
- # Lags

Correlogram
AR Model
Input
Order

Bartlett
Blackman
Hamming
Hanning
Kaiser
Rectangular

Figure 4.1 SPECPAK Menu Selection System
automatically send the correct commands for establishing the digitizing mode. The sampling frequency is set through the software, and the settings regarding the display of the waveform on the screen, triggering parameters, and the HPIB menu settings are established by the user from the scope panel. It is imperative that these parameters are set correctly before attempting an acquisition. The proper settings are as follows:

**TRIGGER PARAMETERS**

- edge triggered
- source - ch1
- noise reject - on
- level - appropriate for signal amplitude

**DISPLAY PARAMETERS**

- norm
- min persistence
- screens - 1
- grid or frame

**HPIB PARAMETERS**

- mode - addressed
- address 7
- EOI off

Triggering refers to the event that causes the scope to start displaying data on its screen. A trigger event occurs when the input signal amplitude reaches a specified "trigger level" set on the front panel of the oscilloscope and it is usually shown as the start of the signal. However, digital oscilloscopes have memory buffers, allowing data before a trigger event to be displayed if desired. In this way, the part of a signal before the trigger event can be seen. This operation is activated through the "delay" value in the front panel.
trigger menu. A negative delay value causes data to be displayed before the trigger event to be displayed and a positive delay value causes the scope to wait before triggering.

Once the scope parameters are set correctly and the triggering is appropriate for the signal, the acquisition subsystem is selected and the sampling frequency entered. There is a slight pause while the scope sets itself, then a "Waiting for trigger .... " notice appears in the window. At this point, when the animal makes an echolocation call and the amplitude of the signal reaches the specified trigger level (preferably high enough to reject ambient room noise but low enough to start near the beginning of the signal), the scope will do a single scan on the channel and the echolocation call will be displayed in the scope screen. The program will download the first 1024 points of the 2000 point digitized signal and compute some statistics on the array, one of which is the mean value of the samples. If the mean value is not zero, some DC or low frequency content will appear in any spectral estimations performed on the signal. This should be overlooked as a remnant of a DC bias from the microphone and amplifier output and not as part of the signal itself. When the statistics are displayed, the acquisition is complete. If the signal acquired is not satisfactory, another acquisition can be performed.

4.2 Utilities

Some file-related functions are necessary for the SPECPAK program to accomplish input/output. In addition, there are many instances where
changing the directory or issuing several DOS commands is required. The utilities available in SPECPAK allow for saving and retrieving data arrays, changing directories, and temporarily exiting to DOS. These functions are accessed through a sub-menu as shown in Figure 4.1.

The save and retrieve utilities allow file I/O for time or spectral data sequences. For example, time data can be retrieved from disk files and results of a spectral estimate can be saved to a file. These functions both work for time or spectral data. Saving data and retrieving data differ only slightly in that retrieving new time or spectral sequences requires the sampling frequency to be input for the data being retrieved. If this input were not available, the spectral plots could have erroneous frequency information on the axis, unless the sampling frequency was the same for the previous data.

The data files are stored in single column ascii format which allows for data importing to other software programs. An example of this is for obtaining hardcopies of the spectral plots. Presently, SPECPAK lacks a graph printing function, so the plots produced by the software cannot be easily transferred to the printer or plotter. The ascii file format allows the data to be imported to a wide variety of programs which can generate the plots and interface with printers.

In addition to saving and retrieving data, the program also has utilities for changing the current directory and exiting temporarily to DOS. These features are useful when the storage of data files in separate directories is desired or a series of DOS commands need to be issued without actually exiting the program.
4.3 Signal Processing

The four signal processing functions take time data and filter it in such a way as to transform the sequence into a frequency domain representation useful for characterization of the signal. Each of these methods use the Fast Fourier Transform algorithm to perform efficient calculations, but the estimation approach is quite different for each.

For the classical estimators, FFT, Periodogram, and Correlogram, a data window is applied in the estimation. In the case of the AR Model, data windowing is not necessary. The window function is selected via a sub-menu activated upon selection of one of the above estimators. If the Kaiser window function is chosen, entry of the alpha value is requested as well. When the desired estimation algorithm is selected and the applicable parameters are entered, the estimator is executed by the software.

4.3.1 FFT - Fast Fourier Transform

When the FFT option is selected, SPECPAK runs a Fast Fourier Transform on the time data array, where the window function is applied to the entire data sequence in this case. The radix-2 decimation-in-time FFT algorithm is implemented and the exponential table required by the FFT is stored in static memory. If the same size FFT is called upon twice in a row, no matter what estimator is applied, the exponential table is already available. This is the fastest estimator available, taking approximately two seconds on a 20 MHz 386 machine. This machine
was used for all benchmarks included in this chapter.

4.3.2 Correlogram

The Correlogram selection calculates the autocorrelation sequence of the time data out to a specified number of lags, applies an optional window to the correlation sequence, and then uses the FFT to transform the windowed sequence into its frequency domain counterpart. When selected, an input form appears asking for the number of lags desired. Then a window function is requested and the Correlogram estimator is executed. An estimation based on 32 lags of the autocorrelation takes approximately 5 seconds.

4.3.3 Periodogram

This selection applies the Welch Periodogram spectral estimator to the time data. This estimator performs FFT's on a specified number of segments of the data, with an optional window function applied, and averages the resulting spectral arrays to arrive at a more asymptotically correct estimation of the frequency spectrum.

When chosen, an input form appears asking for segment and overlap information in percentages. The segment percentage is a number representing the ratio of the desired segment length to the length of the time data array. The overlap percentage is a number representing the ratio of overlap to segment length. After this information is entered, the window menu appears where the desired data window function is
This particular algorithm is the slowest of all the estimators, whenever a large amount of segments is required, since it computes an FFT for each segment. An example is a 10 segment Periodogram which takes approximately 20 seconds.

4.3.4 AR Model

This selection applies the Autoregressive Parametric Estimator to the data using the Burg method for parameter estimation. A specified number of parameters are estimated from the time data and these parameters are used in the FFT to evaluate the frequency domain representation. When selected, an input form appears requesting the order of the process, and then the algorithm is executed. No windows are applied in this estimator.

Selection of an appropriate order for the AR Model is a highly empirical process, a reasonably effective method being to begin with lower orders and examine the changes in the spectra as the order increases. Even though selection criteria are discussed in the literature [1][22], they are not truly applicable in this case, and experience proves to be just as effective.

The speed of the estimation is a function of the model order, with a 10th order estimate requiring about 9 seconds for execution.

4.4 Plotting
The plotting subsystem in SPECPAK provides a graphical display of the data sequences stored in memory. The graphs of the current time or frequency arrays are available through a sub-menu activated when plotting is chosen from the main menu. In addition, another choice is available in the sub-menu for viewing the various data windows. The windows choice is included for the express purpose of viewing the time domain window functions.

The plot routine writes the desired data array to a file on disk, along with an information file called SPECPAK.INF which contains graphing information (axis labels, data file name, etc.). This file is then read into another program which is executed from the SPECPAK program. The data is scaled to the appropriate dimensions of the plotting area, and the plot is drawn on the screen, with full borders, axis tick-marks, labels, and titles.

4.5 Software Notes

All of the programming code for the SPECPAK program was developed under Turbo C++ from Borland, Int'l., Scotts Valley, CA. The C++ extension of the C language was chosen for its ability to handle complex arithmetic using objected oriented techniques and function overloading. From a numerical computation standpoint, FORTRAN would have been a better language (only the newer versions which allow array indexes of zero), but the SPECPAK environment depends so heavily on text windows and menuing routines that C was the desired choice.

Third party libraries, written in C, were very helpful in the
development of the program as well. The functions used for the text windows and data entry are compiled in a library called the "WINDOW BOSS". This very useful set of routines (which also can have full mouse support if desired) is available from Star Guidance Consulting, Inc., Waterbury, Connecticut. The scope interface library was provided by Hewlett-Packard, Inc. These functions are implemented in the module SCOPE.C of the code and execute all the tasks as outlined in section 4.1.

4.6 Conclusion

The integrated analysis and acquisition software discussed in this chapter proves to be a very useful program for a variety of reasons. Three of the advantages are: ease of use, flexibility in application, and simplification of ultrasonic signal analysis. The pop-up menu structure of the SPECPAK program is easily understood and the menu items follow a logical order. With regard to analysis, the flexibility in applying any particular estimator to a signal is very useful. All four estimators presented in chapter two can be accessed through the menu system without special instruction and window sequences are available when appropriate. This flexibility allows the SPECPAK software to be used in other spectral estimation applications. In general, the program provides a simplified means of acquiring and analyzing ultrasonic acoustic signals.
5. EXPERIMENTATION & ANALYSIS

To illustrate the utility of the SPECPAK system, several sequences of echolocation calls from bats were recorded and analyzed. The objectives were four-fold:

1) To decide which estimators performed best for this class of signals.

2) To show that results from SPECPAK compare favorably with existing data on signal characteristics.

3) To evaluate the feasibility of intraspecies and interspecies identification.

4) To discover information not realized with present analysis methods.

5.1 Method and Procedures

Five different bats were observed, with each bat providing from 3 to 11 different acquired echolocation chirps. These five bats represented three different species of Microchiroptera, allowing the investigation of species characterization. In order that the feasibility of identification within species could be studied as well, three of the five individuals were from the same species. Below is a list of the five bats used for experimentation along with their associated common names:
These bats produced a total of 38 sequences for analysis. All signals are shown in appendix B, Figures B.1 through B.38.

The procedure was very simple. With the system operational, the software was started and the DATA ACQUISITION selection chosen from the main menu. A bat was held in front of the microphone and stimulated in some way so as to induce an echolocation chirp. This was accomplished by moving the bat quickly in any direction so as to compel it to reevaluate the surroundings.

The oscilloscope was set in accordance with the specifications in chapter 4 such that when the echolocation signal was detected by the scope, a trigger occurred and the signal was digitized. The software then downloaded the signal over the interface bus and into the computer's memory. At this point, the signal was saved to a file and another acquisition was done. The process was continued until a satisfactory number of sequences were acquired.

5.2 Evaluation of Estimators

Once the signals were saved, the next step was to analyze them using the tools available in the SPECPAK software. As explained in chapter 4, four different types of estimators were available for application in the software. These estimators produced spectral sequences with different properties, each approximating the true PSD.
With some apriori knowledge of the signal characteristics [20], it was possible to gauge fairly well the accuracy of a particular spectrum based on the properties and behavior of the estimation method used. The explanations given for each estimation sometimes include subjective words such as "poor", "undesirable", "useful", "erroneous", etc., and are based on comparisons between known signal characteristics and the estimates produced.

For this class of signals, it is fairly well known [6-9, 12-20], that the spectral characteristics are constant frequency and "narrowband" frequency modulation. Narrowband generally means that the spectral content of the signal is localized to within a specified frequency band. Given this apriori knowledge of the chirp, one might conclude that a parametric approach is more applicable than the classical estimators since the parametric autoregressive estimator performs better in narrowband situations. However, the definition of "narrowband" in the echolocation signal analysis literature is not consistent with spectral estimation literature. In cases where spectral peaks are closely spaced, the signal does not conform to the definition of narrowband as per spectral estimation theory. Consequently, the AR model is shown to perform poorly for these cases.

In this section, each estimation method is applied to the same signal, and judged for performance relative to the known typical characteristics. The signal, shown in Figure B.17, is a typical echolocation chirp from the species, *Eptesicus fuscus*. Almost all spectral plots presented will show some low frequency content. This is caused by a small DC offset in microphone/amplifier subsystem and does
Figure B.17 Echolocation call of *Eptesicus fuscus*

not necessarily reflect any signal content at these frequencies.

With respect to the windowing function applied to the data, an empirical determination of the most appropriate window is not included here as this would detract from the more important issue of finding the best estimator for echolocation signals, and the information is readily attained in the literature. However, Harris [4] recommends a Kaiser window with an alpha of 2.5 for good spectral performance, and is therefore used in the following evaluations unless otherwise stated.

The first estimation method applied to the signal is the standard FFT. Figure 5.1 shows the spectrum produced by this estimator. The known peaks [16][17][20] at 20 and 40 kHz are easily observed in the spectrum. They represent the fundamental frequency emission and its first harmonic. The bat actually generates these frequencies separately. In addition to this, a distinct peak around 60 kHz reveals a second harmonic in the echolocation call. The FFT with a Kaiser window function applied is the most effective estimator for revealing this intermittent portion of the chirp.
To demonstrate the window function effects on the spectrum, an example of the FFT without windowing is illustrated in Figure 5.2. The spectrum has been corrupted by the abrupt truncation of the data at its endpoints. The lower amplitude second harmonic is completely "smeared out" by the closely spaced first harmonic. Therefore, the application of a window is necessary to provide acceptable frequency content resolution.
The spectral curves produced by this estimator are very erratic, or "noisy". This effect is produced when the data sequence length is close to the FFT length. In the case of the SPECPAK program all transforms are 1024 points long, which is exactly the same length as the time data sequence of Figure B.17. If the data were padded with zeros, and the FFT length increased, the spectral estimate would be much smoother.

The Periodogram was also applied to the data and Figure 5.3 shows the results of this estimator with 25% segmentation and no overlap. This translates into four segments being computed and averaged for a final estimate. In this figure it is clear that the Periodogram estimate gives results very different from the FFT estimator. An incorrect conclusion is that the bat is producing four or even five distinct harmonics. The spectrum reveals a weakness in the application of single spectral estimates for signals such as these. Since the signal is known to be frequency modulated to some degree [16],[20], the frequency
content of the signal is changing as time progresses. The Periodogram is picking out this change due to the segmenting operation where the frequency content of one segment is different from the next. This effectively fools the averaging process. Thus the apparently erroneous peaks in the spectrum. The term "erroneous" is correct in the sense that the estimate does not allow for effective reconstruction of the original signal.

It would seem likely that if segmentation were increased, this effect would be less noticeable. The Periodogram estimator with seven segments is shown in Figure 5.4. This is accomplished with a segmentation of 25% and a 50% overlap. In this estimate, the peak revealing the fundamental is still clear, but the first and second harmonics are cluttered and not differentiable. However, the estimate is not producing five distinct peaks anymore, so the increased segmentation does reduce the average-fooling problem.

Figure 5.5 shows the resulting estimate for a 20 segment Periodogram (5% segmentation, no overlap). This data has become very
smooth due to the high segmentation but lacks the resolution of the third peak made manifest in the FFT estimates. It can be concluded then, that the performance of the Periodogram was poor, since increasing segmentation did not produce estimates with better resolution. In addition to this, the length of time required to perform a Periodogram is very undesirable as it is directly proportional to the number of segments involved.

The Correlogram, which has its basis in the application of the
discrete Fourier transform to the autocorrelation sequence, is next to be evaluated. Figure 5.6 shows a 32 lag Correlogram applied to the data and the spectral estimate is seen to bear striking resemblance to the Periodogram estimate of Figure 5.5. The smoothness of this spectral estimate is caused by the short autocorrelation sequence as compared to the FFT length (for \( M \) lags, the autocorrelation sequence is \( 2M+1 \) points long), but as the number of lags increases the estimates become more irregular. Also, the resolution of the estimate is very poor, and the only real information which can be gleaned from the data is that there are two major peaks of interest. Again, the second harmonic revealed in the FFT, is not distinguishable in this estimate. It was expected that as the number of lags was increased, and consequently the amount of information in the autocorrelation sequence was greater, that the estimate would improve.

As shown in Figure 5.7, doubling the number of lags to 64 does not significantly increase the performance of the Correlogram, but does lend
evidence to the fact that increasing the number of lags helps the resolution. Figure 5.8 shows the estimate for 128 lags, and though the performance is better, it is still not an accurate approximation of the

![Spectrum Graph](image)

Figure 5.8 Correlogram - 128 lags

frequency content because the smoothing of the second harmonic is still very prevalent. Since this is a vital part of the frequency information, the Correlogram does not perform appropriately for echolocation signals. Again speed is an unfavorable property of this estimator since the computation of the autocorrelation sequence for even a small number of lags takes longer than the transform.

The last estimator applied to the data is the Autoregressive model. No windowing is implemented in this algorithm. Figure 5.9 shows the results of a third order AR estimate of the data and it would seem to be a very poor performer due to the completely erroneous estimate produced. However, this spectral estimate was produced on the basis of a three point parameter sequence and still generated enough information to indicate major frequency content in the area of 20-60 kHz.

By adding two more parameters to the sequence, the AR estimate
produces the spectrum shown in Figure 5.10, which differentiated two of the three peaks shown by the FFT. Increasing the order to ten gives the AR estimate shown in Figure 5.11, with the second harmonic quite distinguishable. Apparently, increasing the order brings out even greater detail. As shown in Figure 5.12, however, a 20th order estimate produces some undesirable irregularities that are inherent in higher order AR estimates. When the Burg algorithm for computing the parameters is used in the AR model implementation, the estimates produced exhibit this "line-splitting" phenomena [1] for higher orders.
Line-splitting refers to inappropriate division of peaks in the spectra when only one peak exists, or where the signal is frequency modulated. This can make the AR model inappropriate for many, but not all estimation problems.

5.3 Conclusion

It is concluded that the FFT and AR Model estimators are most appropriate in the analysis of echolocation signals of Microchiroptera.
Generally, a good approach is to run the FFT on the data first, and evaluate the resulting spectral shape. In cases where a frequency modulation exists in the signal, the FFT will usually give more useful results, but if the signal is mostly constant frequency, the spectra produced by the AR Model are favorable.

The papers by Simmons, et al. [16],[20] provide information on previous findings regarding spectral content of bat echolocation calls. The figures presented in these papers for the species *Eptesicus Fuscus* indicate two peaks (one actually indicates a third low energy peak as well) near the frequencies indicated by SPECPAK data. From this information, the spectral estimates produced by SPECPAK can be seen to compare favorably with currently accepted data.
6. CHARACTERIZATION AND IDENTIFICATION OF MICROCHIROPTERA

The feasibility of identifying a particular species of bat by the spectrum of the echolocation signal emitted is one of the interests of this project. A good deal of work has been done in this research area using a variety of methods but, digital spectral estimation techniques have been neglected. In this chapter, the present methods for bat characterization are reviewed. This is followed by application of the FFT and AR Model estimation methods to several of the acquired signals illustrated in appendix B. As shown in chapter five, these techniques are shown to be more appropriate than others for this class of signals. Results of these analyses are presented.

6.1 Present Characterization Methods

The overwhelming majority of work in this field is presently based on tracking the spectral peaks as a function of time. This produces a set of patterns much like those illustrated in Figure 6.1 for three different species of Microchiroptera. These patterns are labeled as combinations of long and short sections of constant frequency (CF), frequency modulated (FM) components. If a signal is classified as long-CF/FM, this means that the chirp starts with a long constant frequency tone and finishes with frequency modulation.

The patterns form a set of classes for echolocation signals as defined in [20]. In this paper, Simmons, et al. present these patterns of signals as a basis for characterizing the particular bat. The author
Figure 6.1 Representations of sound spectrograms illustrating three commonly observed types of echolocation sounds used by bats. (Figure borrowed from [20].)

lists 18 bat species along with an associated typical constant frequency component of the echolocation signal. He also describes, in figure form, the characteristics of bat sonar echoes in the frequency domain for a variety of species. In another paper [16], Simmons makes the case for the sufficiency of "seven acoustic dimensions" for distinguishing typical sonar signals of twenty-five different species of echolocating bats. These classification procedures have been very effective in the study of bat sonar, but since each component in the analysis system is isolated from the others [19], the method used to obtain the frequency data is very time-consuming and repetitious.

The characterization of echolocation signals by tracking frequency content peaks requires a type of analysis known as a spectrogram. This representation shows the spectrum for several sections of the time signal incremented in time. The signal might be divided into twenty sections and spectral estimates of each successive section produced.
The frequency content is then plotted for each section in a "waterfall" arrangement and the change in the signal spectra for successive time bins can be observed. Simmons [13] gives a very thorough example of the use of the spectrogram for analysis of Free-Tailed Bats. This analysis can be done very efficiently with digital methods, and could easily be implemented in the SPECPAK software in the future. However, the capabilities of the present SPECPAK system allow other important aspects of the spectrum such as detailed harmonic content, bandwidth, and sharp spectral peaks to be observed. This analysis forms the basis for a decision on the feasibility of interspecies and intraspecies characterization of bats.

6.2 Classification and Identification using SPECPAK

Much of the present echolocation research is devoted to the study of entire echolocation bursts [12,14,15,17,18]. A burst is a series of chirps that the bat emits with varying repetition rates depending on the activity. This work is concerned with the analysis of one single chirp. The spectral estimation methods available in the SPECPAK software allow the researcher to look at the content of a single chirp in its entirety. In this way it is possible to evaluate the signal in more detail.

In the previous chapter, the four spectral estimation methods were evaluated for applicability to single echolocation chirps. It was decided that the best techniques for bringing out the spectral content accurately were the standard Fast Fourier Transform with a Kaiser window function and the AR Model. This is essentially the third goal of this
research; to study the feasibility of distinguishing one species of Microchiroptera from another or one individual from another based on the frequency content, produced by these estimators, of the echolocation call.

6.3 Application of Appropriate Estimation Models

Nineteen acquired signals from Appendix B are analyzed with the FFT and AR estimators, and the interesting spectral properties are discussed. Every signal in appendix B was examined using the SPECPAK software, but the cases presented were chosen as a representative sample of the results. The order for each AR estimate was chosen based on the results of many experiments in which the spectral information was optimized. Thus the order for these estimates vary from 7 to 15 depending on what was required for best estimation performance. The best estimation result is the one which effectively models the known peaks in the spectra, and does not have any observed line-splitting phenomena. In some cases, where only one estimator is shown for a particular signal, the other estimator was ineffective in producing useful spectra and is not included. For the AR estimates of the Pteronotus, the exact frequencies of the peaks are included in the discussion. This is the only case where exact frequencies are appropriate, since the rest of the bats exhibit strong FM components in their echolocation calls, causing biasing of the spectra when the entire sequence is analyzed.
6.3.1 Pteronotus parnellii

The first bat to be evaluated is from the species *Pteronotus parnellii*. Seven different echolocation signals for this species are illustrated in appendix B, Figures B.1 through B.7. Figure 6.2 shows an FFT spectrum for the first signal in the set (fig. B.1). This frequency domain representation is very different from the spectra produced for the *Eptesicus fuscus* signal in chapter five. The narrow, sharp peaks in the spectrum indicate the presence of pure sinusoidal tones in the bat's echolocation call and is indicative of the constant frequency (CF) component in signals emitted by the *Pteronotus*. It should be noted that this animal is known for a CF/FM call, and the signal was truncated before completion of the chirp. The FM portion of the signal was lost in the acquisition and therefore is not manifested in the spectrum. The ramifications of this are discussed in chapter seven.

The center frequencies of the peaks are very identifiable at 60
and 90 kHz, but there is some question about a peak at 30 kHz. Applying the AR estimator with order 10 yields Figure 6.3, which shows definite peaks at 30.27, 60.55, and 90.3 kHz. The good peak detection characteristics of AR model spectra makes finding the exact frequency of the peaks much easier, and is one reason why this estimator is useful.

![Figure 6.3 AR (order 10) for fig. B.1](image)

The features of the spectrum for the constant frequency portion of the signal could also prove to be very effective in the identification of the *Pteronotus* species.

Figure 6.4 shows the FFT for the second signal in the *Pteronotus* set (fig. B.2). This plot is practically identical to Figure 6.2. Note again the questionable peak around 30 kHz in the FFT spectrum. The AR estimate in Figure 6.5 again details the features more clearly, revealing a very definite peak at 29.79 kHz, along with the major peak at 60.79 kHz and second harmonic at 91.06 kHz.

Applying the estimators to Figure B.4 yields similar results for the same bat. As seen in Figure 6.6, the same peaks are evident at 60 and 90 kHz, and the peak at 30 kHz which was questionable in the
previous FFT estimates is obvious here. However another apparent harmonic at 120 kHz should be noted. As Figure 6.7 shows, the AR model does little to confirm any information in this range, due to the inherent poor estimation properties near the Nyquist frequency. The existence of a fourth harmonic has previously been identified in this species so the indication of spectral content at this frequency is valid.

The echolocation signal in Figure B.7 is also from the same *Pteronotus* bat, however, its time domain features differ greatly from
the rest of the signals. This illustrates the ability of the bat to change the properties of its echolocation call. An FFT analysis of this signal is shown in Figure 6.8. The wider peaks, characteristic of an FM waveform, replace the narrow ones of the previous spectral estimates, and the apparent center frequencies have been shifted down somewhat. However, even though the spectral information has changed a great deal for this signal, the characteristic three peaks are still present. Figure 6.8 reveals again a very low amplitude fourth peak which also showed up in the spectra of Figure 6.6.
Looking at the AR model estimate of Figure 6.9, the fourth peak is not made manifest. However, if the order is increased slightly to 13, as in Figure 6.10, all four peaks become well defined at 25.15, 51.27, 80.32 and 109.86 kHz respectively. There is definitely a third harmonic being produced by the *Pteronotus*.

Analyzing other signals from the same bat yields very similar results, lending credence to the idea that the *Pteronotus* species is
definitely classifiable using these methods.

6.3.2 Macrotus

The second Microchiroptera species studied in the experimentation is the *Macrotrus macrotus* which generated the signals in Figures B.8 through B.16. The short duration of the time domain signal is characteristic of this species. The animal belongs to a class of bats called "Whisper Bats", due to the low amplitude of the echolocation signal. This causes extreme difficulty in the spectral analysis, since the signal to noise ratio is much lower than other species.

Figure 6.11 illustrates an FFT spectral estimate for the signal of Figure B.8. This estimate reveals the existence of two main peaks around 40 and 75 kHz spaced well apart. The AR model shown in Figure 6.12 verifies this information with peaks around 38 and 72 kHz.

The analysis of the *Macrotus* signal of Figure B.11 produces somewhat differing spectra from the previous signal. The FFT estimate
in Figure 6.13 shows three more closely spaced peaks, the third of which is very low amplitude. It is possible that the bat has changed the structure of the echolocation signal for some reason, but due to the nature of the estimator behavior on FM signal components, a conclusion would be inappropriate. The AR estimate for this signal, Figure 6.14, shows the peaks more clearly. Due to the low amplitude of the third peak in the spectra, the order of the AR estimate was increased to 13 for this signal.

The FFT estimate for the signal of Figure B.15 is shown in Figure
6.15. Obviously, the frequency content is not similar to either of the previous *Macrotrus* signals. In the FFT, it is impossible to distinguish whether there is more than one peak present. If there are multiple peaks in the spectrum, the frequency modulation is so prevalent that the transform properties tend to smear the estimate.

The AR model, shown in Figure 6.16, fails to give any conclusive information either, and the small low frequency peak implies a harmonic there but the evidence is not convincing. The fact is, FM components in these echolocation calls are generating spectra that do not reveal
accurate information, and is therefore difficult to characterize with any of these estimation methods.

Looking at one last signal from the Macrotus species, Figure B.16, some similarity to the previous signal is displayed, both in the time and frequency domains. Figure 6.17 shows the FFT for this signal, with the two major peaks closely spaced around 60 and 85 kHz. No other information can be gleaned from this graph.

The AR model estimate for this signal brings out some detail on the center frequencies of the peaks, and also supports the existence of
very small humps as referred to above. This low frequency content was also alluded to in the previous AR spectrum. The order of this estimate had to be increased to 15 in order to obtain the detail shown. However, any greater increase caused the spectral line splitting phenomena, so this is the best estimate available.

In general, the Macrotus spectral characteristics were very indeterminate. There are at least three possible reasons for this. The low amplitude of the signal does have a definite effect on the estimator's ability to extract useful information. The bat could also
have been emitting spectrally varying signals. Or the estimators could be inappropriate for the signals. In all likelihood, the problem here is a combination of all three. In any case, successful characterization of Macrotus species based on the present SPECPAK analysis tools is unlikely.

6.3.3 Eptesicus fuscus #1

The next three animals to be analyzed are all from the *Eptesicus fuscus* species, whose local native habitat makes them easily accessible and ideal for study. The signals in appendix B numbered B.17 through B.38 are echolocation signals from these bats, of which Figures B.17 through B.27 apply to *Eptesicus #1*, B.28 through B.35 apply to *Eptesicus #2*, and B.36 through B.38 apply to *Eptesicus #3*. Generally, the time domain signal for these bats is about 3-4 milliseconds in duration so most of these signals fit in the time limit for digitization with little truncation.

Chapter five concentrated on Figure B.17 for the evaluation of the estimators, so there is no need to include it here. However, the strong second harmonic is significant, as it does not appear in any of the following signals for *Eptesicus #1*.

Figure 6.19 shows the FFT estimate for the signal of Figure B.19, where the data indicates only two major frequency peaks. The first peak which is very defined, and consistently appears in spectra for this species, will be noticeable in most of the following estimates. The AR spectrum is not included for this signal as it produced unsatisfactory
The signal in Figure B.21 produces the FFT estimate shown in 6.20. The data is very similar to the previous FFT estimate and the second peak is still very ambiguous.

Figure 6.21 shows the 10th order AR estimate for this echolocation chirp. The three distinguishable peaks have little in common with the FFT estimate. With approximate peak frequencies of 35, 50, and 75 kHz, they also do not appear to be consistent with the evenly spaced
harmonics of other Eptesicus spectra. In this case of this indicated frequency modulation, it seems as if the AR estimate will not yield useful results.

Figure 6.22 shows the FFT estimate for figure B.22. The spectra reveals a similarity to the above signal in the smearing of the second peak(s). This signal is very similar in the time domain as well, except for a slightly lower amplitude. A fifth order AR process was run on the signal producing the plot of Figure 6.23. This AR estimate is much more
consistent with the FFT, which may be indicating that lower order AR Models give better spectral estimates for frequency modulated signals.

Finally, an FFT estimate for Figure B.24 is shown in 6.24. This
time domain signal differs somewhat from the others presented here, but the spectra are surprisingly similar. The first spectral peak is more wideband than in previous signals, but the general characteristics are the same.
6.3.4 *Eptesicus fuscus* #2

The next animal to be examined is the second bat in the *Eptesicus fuscus* species. Figures B.28 through B.35 are from this bat and these time domain signals differ significantly from the signals of *Eptesicus fuscus* #1.

The spectrum of Figure 6.25 is produced by an FFT of the signal in B.28. Predictably, due to the relatively low signal amplitude with respect to the ambient noise, the peaks do not present themselves in the FFT very strongly. But there are at least two definite crests in the spectral data.

Application of a 10th order AR model gives the estimate of Figure 6.26. The two peaks are made manifest very distinctly here but the center frequencies do not coincide with the approximate center frequencies in the FFT. This is another anomaly in the AR process: for situations like this, lower order estimates must be used to reduce line-
splitting, but the cost is a frequency bias on peaks of lower amplitude. The problem is caused by the frequency modulation of the signal and consequent violation of the wide-sense stationarity assumption made in the Periodogram, Correlogram, and AR Model estimators. In evaluating FM signal components, the AR Model will not give accurate results.

Figure 6.27 is the AR estimate for the signal in B.32. The two spectral peaks are easily observable and compare favorably with other signals of the same species. The center frequencies of the peaks have
shifted somewhat, indicating the ability of the bat to change the frequency content of its echolocation call. Figure 6.28 is the AR

![Graph](image)

**Figure 6.28** 8th order AR Model for figure B.33

estimate for the signal in B.33. Again, the two peaks are discernable as genuine spectral content.

The last signal to be analyzed for *Eptesicus fuscus* #2 is Figure

![Graph](image)

**Figure 6.29** 8th order AR Model for figure B.34

B.34. The eighth order AR estimate for this signal is shown in 6.29, with spectral features predictably similar to the previous signals of
this bat. In general, although the signals of *Eptesicus* #1 are
decisively different from #2, the results suggest that the bat can be
identified based on the spectral estimation data.

6.3.5 *Eptesicus fuscus* #3

The signals of Figures B.36 to B.38 belong to the third bat in the
*Eptesicus* species. These compare quite well with the time domain
signals of *Eptesicus fuscus* #1, and the spectral estimates will
substantiate the comparison through similar frequency domain features.
AR Model estimates for this bat were not useful due to the strong FM
component in the signals and are not included here.

Figure 6.30 shows the FFT estimate for B.36. This spectral
estimate again reveals a second harmonic in the signal for the *Eptesicus*

![Figure 6.30 FFT for figure B.36](image)

*fuscus* species. Though considerably lower amplitude, the peak is still
very distinguishable.
Figure 6.31 FFT for figure B.37

Figure 6.31 shows the FFT estimate for B.37. As expected, the spectrum contains the two major peaks around 30 and 60 kHz, but the third peak exhibited in the previous spectrum is not manifest as strongly in this estimate.

Figure 6.32 FFT for figure B.38

The last signal of appendix B, Figure B.38, again has similar features in the frequency domain. Figure 6.32 shows the FFT for this signal, and the spectral properties are very consistent with previous signals of the same species. The second harmonic is not detected in
this estimate and the gradual decrease in the energy of this harmonic implies that the animal was choosing to stop generating it.

6.4 Conclusion

It has been shown that digital spectral estimation methods applied to signals of Microchiroptera produce very useful information. All estimators perform differently in this application and the AR Model and FFT have been deemed most useful for this particular method of application. For signals with mostly CF components, the AR Model provides a very good peak for exact frequency information. When FM components are prevalent, the FFT performs better since it is not biased by stationarity assumptions.

Generally, a distinguishable frequency domain representation of the signal is produced with these methods and the implication is that intraspecies classification using these methods is feasible with intelligent application of the signal processing algorithms. However, identification within species using the methods presented is not possible due to the similarities of spectra from one bat to another.
7. RESULTS AND CONCLUSIONS

It is apparent that the frequency domain properties of Microchiroptera echolocation signals can be distinguishable when produced by the digital spectral estimation methods presented. The results indicate that digital signal processing methods can be of significant value in understanding animal echolocation, and with some enhancement to the system, it is very probable that bats and other animals will be successfully characterized by the "acoustic print" they possess.

7.1 Spectral Estimation

Each spectral estimation algorithm has properties which determine its applicability to the data at hand; speed, accuracy, frequency resolution, and spectral shape to name a few. In addition to the estimator's analytical properties, the theory behind the algorithm is significant because it determines what assumptions are made regarding the data. One difficulty with all the methods based on random processes is the assumption that the signal is wide-sense stationary. In the case of frequency modulated signals, which bats generally produce to one degree or another, this assumption is invalid. The estimators are still very useful for spectral analysis, but care must be taken to interpret the results correctly based on the behavior of the estimator being applied.

In chapter five it was concluded that the FFT and AR Model
estimators were most appropriate for analysis of echolocation signals. However, each method is useful for different aspects of the investigation. If the signal has an FM component, the FFT is useful since its good spectral shape behavior reliably represents the full set of frequencies in each harmonic as well as other signal anomalies. When specific frequency information is desired, as would be the case in a CF portion of the signal, the AR Model is the method of choice since the "peaky" spectra allow more accurate readings from the graph.

Chapter six revealed that, based on the results of these estimation methods alone, characterization across species is possible, but that interspecies identification is not. The estimates for 19 signals from five different bats were presented and the conclusion was made that the spectra do include useful information, but that a time-dependent evaluation is neccessary for effective analysis.

7.2 Recommendations For Future Enhancements

Although the results produced from SPECPAK are significant, and have definite scientific application, the system is not truly useful in the present state except for laboratory work. The ideal system would be contained in a laptop computer, combining the data acquisition system, amplifier, preamplifier, and microphone assembly into a single unit. With this portability, one could easily go into remote locations and sample the acoustic signals of Microchiroptera in their natural environment, giving a more accurate picture of the sounds which they emit under normal circumstances. The ideal system was not accomplished
in this work. However the present system lays the groundwork for future research which should be able to accomplish the goal successfully.

Some enhancements to the system should be considered for more effective operation. For instance, the microphone used in this system is a 1/4" Brüel and Kjær transducer which has accurate frequency response up to approximately 100 kHz. For some bat species, this is inadequate as the frequencies present in their echolocation calls can be as high as 150 to 200 kHz. In order to preserve the integrity of signals such as these, a microphone with wider bandwidth ( > 200 kHz ) should be used.

The limited memory in the digitizing oscilloscope is another restriction on the system since it can only hold 2000 points of data in any one acquisition set. The scope memory limitation is not an issue at present since the SPECPAK software is does not support more data records over 1024 points, but the duration of the signal is constrained regardless. Any sampling frequency can be chosen, but with a resulting decrease in available signal duration. This limitation presently prevents the SPECPAK software from analyzing the echolocation calls of some tropical bats whose signals have long duration and high frequency. However, since the memory limitations of the software are correctable through more efficient program code and intelligent use of the compiler, the real issue is the 2000 point limitation in the scope.

It is recommended that the acquisition subsystem be modified to support a very high speed ( ≥ 1 MHz sampling rate ) A/D card which attaches to the PC motherboard bus, and has direct memory access (DMA) capabilities controlled directly by the software. The card would also
need a "pre-trigger" buffer system for storing a number of points before the trigger event, so that the entire waveform can be captured. This A/D add-in circuit would remedy the memory limitations and also eliminate the need for a digitizing scope, addressing a critical portability issue.

The amplifier unit is also not conducive to a portable system. If a laptop computer is to be used for the controller, an amplifier should be designed which would interface directly with the computer for gain control. The signal would be translated to voltages by the microphone, boosted by the amplifier, then digitized by the A/D circuit; all within the PC.

Other enhancements are recommended as well. In order to achieve real-time audible feedback, a signal playback subsystem could be implemented, which would involve a frequency shifting operation and a digital-to-analog conversion played through an appropriate speaker. This would allow the scientist to listen to an acquired signal, thereby creating another mode of signal evaluation.

Three enhancements related to the software would be appropriate: those being spectrogram analysis, graph printing, and availability of multiple file I/O formats. The spectrogram, currently implemented in modern echolocation signal analysis, is not supported by SPECPAK. From the results of the experimentation, it has become clear that the spectrogram essential to appropriate frequency domain representation of Microchiroptera echolocation signals. This type of analysis allows the frequency content of the signal as a function of time to be observed and produces data which can be displayed in several ways, either by the peak
tracking format of Figure 6.1, or a "waterfall" arrangement where the full spectral amplitude content is preserved. For effective bat characterization, this enhancement is a requirement.

In addition to strengthening the analysis section, a utility for printing graphs would be beneficial. The software currently does not allow printing of graphs directly, and this limitation has proven very restrictive. A printing utility could be implemented with printer drivers or at the very least, a function for creating graphics files in HPGL (Hewlett Packard Graphics Language) format. This format is a software graphics standard and would allow the plots from SPECPAK to be imported into other software packages for printing.

Different file formats other than single column ASCII would also be very useful for more flexible data transfer. Some possible formats are single column binary and binary matrix, both of which produce files less than half the size of the current ASCII files and are transferred at ten times the speed since no conversion is necessary.

7.3 Summary

A system was developed which allowed efficient spectral analysis of the echolocation calls of Microchiroptera using digital signal processing techniques. Each spectral estimator was evaluated for performance based on the signals of interest, and conclusion made regarding the most appropriate algorithms. Echolocation signals from several bats were acquired and the spectral properties examined for feasibility of interspecies characterization and intraspecies
identification.

The system performed extremely well as an integrated signal acquisition and spectral analysis package and the results produced by the estimators gave reasonable insight into the spectral characteristics of echolocation signals. Even though the signal processing algorithms proved to be less than adequate for the class of signals studied, it does not take away from the functionality and simple operation of the SPECPAK software, or the capability for application to other digital spectral estimation problems.

If the recommended enhancements are made to the system, a significant advance in the study of animal behavior by uncovering secrets that lie in the discernment of their acoustic signals is anticipated. Better physiological and neurological explanations for the echolocation capabilities of Microchiroptera should be obtained based on analyses accomplished with the digital spectral estimation methods. The result will be a professional quality signal analysis package providing scientists of many disciplines with a powerful research tool.
APPENDIX A. SPECPAK User Guide

A.1 Overview / Main Menu

At the DOS prompt, with the SPECPAK files in the current directory, type "WSP" and hit ENTER. The SPECPAK program will begin with a screen showing the main menu. There are five choices at this point; DATA ACQUISITION, UTILITIES, SIGNAL PROCESSING, PLOTTING, and EXIT. In general, the user will want to begin with either DATA ACQUISITION or UTILITIES/RETRIEVE, in order to get data into the program for analysis. After a time sequence has been obtained, the next step is to look at the time data. This is done through the PLOT menu. Once the user is satisfied that the data is acceptable, the SIGNAL PROCESSING menu item is selected and another menu appears asking for the desired analysis algorithm. The user should select the routine of their choice and then enter any specifications if applicable. Depending on the estimator chosen, another menu will appear asking for a choice of data windows to apply to the time sequence. The user is advised to read chapter 2 thoroughly for an understanding of how the windows are being applied. The computer will then run the selected estimator on the time data and produce a spectral data sequence which should (?) describe the frequency domain representation of the signal. Hitting the ESCAPE key transfers the program back to the main menu, where, if the user desires to see the spectral data in a graph, the PLOT menu should be selected and SPECTRAL DATA chosen. The user can now go back and get a different signal to work on, pick another analysis algorithm, another window, etc. Any
order can be followed with respect to analysis, but the user is cautioned to remember that no analysis can be done if there is not a time sequence in memory to work on. When finished, quitting the program is accomplished through the EXIT SPECPAK option. All the facilities are discussed in detail below.

A.2 Data Acquisition

Most settings regarding triggering parameters and the display of the waveform on the oscilloscope screen must be set on the front panel before attempting an acquisition, but the user must enter the desired sampling frequency from the software. This value is sent via HP-IB command to the oscilloscope where the appropriate digitizing parameters are set. It is imperative that the user set the proper trigger, display and HPIB parameters:

TRIGGER PARAMETERS

edge triggered
source - ch1
noise reject - on
level - appropriate for signal amplitude

DISPLAY PARAMETERS

norm
min persistence
screens - 1
grid or frame

HPIB PARAMETERS

mode - addressed
address 7
EOI off
Once the scope parameters are set correctly and the user is satisfied that the triggering is appropriate for the signal, the sampling frequency is entered via the DATA ACQUISITION window. A slight pause will be noticed while the scope sets itself, then a "Waiting for trigger .... " notice will appear in the window. At this point, when the animal makes an echolocation call and the amplitude of the signal reaches the user-specified trigger level (preferrably high enough to reject ambient room noise but low enough to start near the beginning of the signal), the scope will do a single scan on the channel and the echolocation call will be displayed in the scope screen. The program will download the first 1024 points of the 2000 point digitized signal (see sec. 4.1.1) and compute some statistics on the array, one of which is the mean value of the samples. (If the mean value is not zero, the user will notice some DC or low frequency content in any spectral estimations performed on the signal. This should be overlooked as a remnant of a DC offset from the scope display and not part of the signal itself.) When the statistics are displayed, this signals the end of the acquisition and the user can go on to the next step. If the signal acquired is not satisfactory, another acquisition can be performed.

A.2.1 Present Data Acquisition Issues

There are some limitations to the acquisition system as it stands presently. The most prevalent issue is the fact that there are a maximum of 2000 points which the scope can digitize in any one sampling session. The issue is complicated even further since the SPECPAK
program can only operate on 1024 point signal sequences due to the inherently large memory requirements of some of the estimators. This is not a major issue for bats whose major frequency components lie in the range of 30 - 90 kHz, with relatively short duration, but does play a part if the user is interested in the analysis of some tropical bat species whose frequency components are in the hundreds of kHz with very long (some over 30 ms) duration. Adequate sampling of these signals would require a 600 kHz sampling rate and 18000 samples to catch the entire signal. This is presently a prohibitive specification.

A.3 Utilities

The next main menu choice after DATA ACQUISITION is called UTILITIES. This menu item allows the user to do a variety of useful things during the program, including saving data arrays, retrieving data arrays, changing the current directory, and running a DOS shell. These utilities are available in a pop-up menu which appears when the UTILITIES choice is selected.

A.3.1 Save and Retrieve

When the user desires to save or retrieve data sequences to or from files respectively, the SAVE and RETRIEVE utilities accomplish the task. Typically, one would acquire a data sequence through ACQUISITION and then SAVE it to disk. Later, stored data sequences can be retrieved from disk for future analysis. The SAVE and RETRIEVE utilities differ
only slightly in that the RETRIEVE function includes a field in the input form that allows the user to enter the sampling frequency used on the data being retrieved. If this input were not available, the spectral plots would have erroneous frequency information on the axis. To use these facilities, the user simply selects the action desired, and fills in the information on the input form. The first field in the form is the data sequence type. This field requires either a T or S, specifying time or spectral data. No other input is valid here. The next field is the name of the data file, which should include a DOS path if the file is not in the current directory or on the currently logged disk. As stated above, the RETRIEVE option includes a third field which allows for sampling frequency input. This is the sampling frequency that was used to generate the data file being retrieved.

Once the input form is completed, the user hits the ENTER key and the data should be transferred. These functions effectively allow for multiple analyses in the same session.

A.3.2 Set Default Directory

This option allows the user to change the current DOS directory without leaving SPECPAK. This feature proves to be very useful when multiple acquisitions are being performed and some organization to the data is desired. The user can save files to different directories this way and avoid the long path names that would otherwise be required in the SAVE filename field. When chosen, this function brings up a data entry form which shows the current directory and asks the user for the
new directory. The 'New Directory' field initially holds the string for the old path, but can be edited using the normal editing keys (HOME, END, INS, DEL, LARROW, RARROW). When the new path is entered, the user hits ENTER and the change will take place. The SET DEFAULT DIR option is also useful when retrieving data files from a floppy disk when the program is being run from a fixed disk. The user simply changes the default directory to the floppy drive and all files will automatically be retrieved from there, again avoiding long path names.

A.3.3 DOS Shell

The DOS SHELL option allows the user to start another command processor as a child of the parent process, SPECPAK, in order to issue DOS commands while keeping the program in memory. This facility is useful when copying or deleting files, checking directory listings, viewing documents, or in some cases, running another program temporarily. When the function is selected, the SPECPAK screen disappears and the DOS command prompt is displayed along with a message to "Type 'EXIT' to Return to SPECPAK." When finished issuing DOS commands, the user simply types the word 'EXIT' and the SPECPAK program resumes with all data intact.

A.4 Signal Processing

The signal processing algorithms are the heart of SPECPAK. These four processes take time data and filter it in such a way as to trans-
form the sequence into a frequency domain representation which can be used for signal analysis. Each of these algorithms uses the Fast Fourier Transform to perform efficient calculation of the spectrum, but they each approach the sampled data from different perspectives. The user simply selects the algorithm of choice and the appropriate transform gets implemented. Some information is needed by each algorithm, though, to complete the process. This information is detailed below, with all input forms defined.

A.4.1 FFT - Fast Fourier Transform

When the FFT option is selected, SPECPAK runs a Fast Fourier Transform on the time data array. Upon selection, the window function sub-menu is opened, and the user should pick the data window of choice from the list. Once the necessary information has been selected, the window array is multiplied by the data array at each sample point and the FFT is executed on the new array. When finished, control goes back to the SIGNAL PROCESSING menu where the user can either hit ESC to go to the main menu or do a different estimator. If the latter is chosen, however, all previous frequency domain information is lost. This is the fastest estimator available.

A.4.2 Periodogram

This selection allows the user to implement the Welch Periodogram method of spectral estimation on the time data. The basic idea behind
this estimator is to perform an FFT on several segments of the data with a optional window function applied, and average the resulting spectral arrays to arrive at a more asymptotically correct estimation of the frequency spectrum. The details of the estimator are given in chapter two.

When chosen, an input form appears asking for segment and overlap information in percentages. The segment percentage is a number representing the ratio of the desired segment length to the length of the time data array. The overlap percentage is a number representing the ratio of overlap to segment length. After this information is entered, the window menu appears and the user should select the desired data window function. This window gets applied to each segment in the periodogram as described above and in chapter 2.

Once the window is selected, the Periodogram algorithm is executed and the spectral array gets filled with the new data, and control transfers back to the SIGNAL PROCESSING menu for further instruction. Again, at this point, the user can go to the main for plotting or choose another estimator. This particular algorithm is the slowest of all the estimators, especially for a large amount of segments or high overlap, since it computes an FFT for each segment.

A.4.3 Correlogram

This selection applies the Correlogram estimator to the time data. In short, the Correlogram calculates the autocorrelation sequence of the time data out to a specified number of lags, applies an optional window
to the correlation sequence, and then uses the FFT to transform the windowed sequence into its frequency domain counterpart. When selected, an input form appears asking for the number of lags desired. Then the window menu appears and a window function is chosen from the list. At this point the Correlogram estimator is executed and control transfers back to the SIGNAL PROCESSING menu.

A.4.4 AR Model

This selection applies the Autoregressive Parametric Estimator to the data using the Burg method for parameter estimation. A user specified number of parameters are estimated from the time data and these parameters are used in the FFT to evaluate the frequency domain representation. This method is highly order dependent.

When selected, an input form appears asking for the desired order of the process. Once chosen, the algorithm is executed and control is passed back to the SIGNAL PROCESSING menu. No windows are applied in this estimator.

A.4.5 Data Windowing

Although this subject is discussed in detail in chapter 2, it should be addressed here as it relates so intimately with the material. The user should take caution in the application of different windows regarding the validity of the results obtained. In as much as it is very easy to try different scenarios using the SPECPAK interface,
actually believing the data takes more intelligent decisions about the application, the signal characteristics, etc. In effect, what is available in SPECPAK is an effective analysis tool with the power to deceive.

Each spectral estimation method mentioned above uses windows in different ways. One estimator applies the window function to the whole sequence. Another only applies the window to a subset (segment) of the sequence at any one time. And another applies the window, not to the sequence itself, but a filtered version of it (M lag autocorrelation). These differences are extremely important and should be considered during analysis.

A.5 Plotting

The PLOTTING selection under the main menu lets the user see in graphics form, the graphs of the current time or frequency arrays. In addition, another selection is available for viewing the various data windows. This selection is included for the express purpose of seeing what the signal actually is that is being used in the estimation algorithms.

When PLOTTING is selected, a menu appears with three choices: TIME DATA, SPECTRAL DATA, and WINDOWS. The user picks the desired choice and the plot is shown on screen. Actually, the process of displaying the graph is much more complex but this is transparent to the user.

Internal to the SPECPAK program, the plot routine writes the selected data array to a file on disk, along with an information file
called SPECPAK.INF which contains graphing information (axis labels, data file name, etc.) The routine then runs a child process in which the graphing is done (external to the SPECPAK program) through a program called 'GRAF.EXE'. When the user is finished looking at the graph, the child process is terminated and control sent back to the PLOT menu.

A.6 SPECPAK Code Notes

All of the programming code for the SPECPAK program was developed under Turbo C++ from Borland, Int'l. The C++ extension of the C language was chosen for its ability to handle complex arithmetic using objected oriented techniques and function overloading, as well as providing a vast array of input/output capabilities. From a numerical computation standpoint, FORTRAN would have been a better language (only the newer versions which allow array indexes of zero), but the SPECPAK environment depends so heavily on text windows and menuing routines that C was the desired choice. In addition, the author was able to appropriate third party libraries, written in C, which were very helpful in the development of the program.

A.6.1 Third Party Libraries

The functions used for the text windows and data entry are compiled in a library called the "WINDOW BOSS". This very useful set of routines (which also can have full mouse support if desired) was authored by Phil Mongelluzzo, of Star Guidance Consulting, Inc.,
Waterbury, Connecticut.

The scope interface library was provided by Hewlett-Packard, Inc. These functions are implemented in the module SCOPE.C and execute all the tasks as outlined in part 2 of this chapter.

A.6.2 Code Specifics

Several items are noteworthy regarding the structure of the SPECPAK code files. There are ten separate modules in all, each of which can be compiled (not linked or executed) alone to form object code. These object modules are linked together along with the above libraries to form the executable file WSP.EXE. This program is stand-alone and requires no overlays (presently) to operate. It does produce two files which are used by the plotting program, GRAF.EXE. These files (SPECPAK.PLT and SPECPAK.INF) are the data and plot information files respectively, for the graphing option.

Inside the code, though the typical user need not be concerned with it, the person wishing to modify or add to the code should know some basic information regarding the programming style chosen.

There are four large data arrays which hold the time and spectral information in real and complex form. These arrays are declared global in the main module and are consequently visible to the entire set of modules at link time. This effectively eliminated the need to pass these parameters in and out of every subroutine. Also there is a #include file called SPECPAK.H which is contained in every module. This file holds other global information (maximum length of data arrays, data
window constant identifiers, global structures, etc.) which must be accessible by all routines in all modules.
APPENDIX B.

ECHOLOCATION SIGNALS FOR 5 DIFFERENT BATS OF 3 DIFFERENT SPECIES
Figure B.1 Pteronotus Parnelli - 1

Figure B.2 Pteronotus Parnelli - 2

Figure B.3 Pteronotus Parnelli - 3

Figure B.4 Pteronotus Parnelli - 4
Figure B.17 Eptesicus Fuscus #1 - 1

Figure B.18 Eptesicus Fuscus #1 - 2

Figure B.19 Eptesicus Fuscus #1 - 3

Figure B.20 Eptesicus Fuscus #1 - 4
Figure B.21 Eptesicus Fuscus #1 - 5

Figure B.22 Eptesicus Fuscus #1 - 6

Figure B.23 Eptesicus Fuscus #1 - 7

Figure B.24 Eptesicus Fuscus #1 - 8
Figure B.32   Eptesicus Fuscus #2 - 5

Figure B.33   Eptesicus Fuscus #2 - 6

Figure B.34   Eptesicus Fuscus #2 - 7

Figure B.35   Eptesicus Fuscus #2 - Communication Call
REFERENCES


