Apparatus for Research on Animal Ultrasonic Signals

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Frontispiece: Some of the equipment described in this paper, including: A — portable oscilloscope (Non-Linear Systems MS-15 Miniscope); B — period meter (Fig. 12) with ultrasonic amplifier (Fig. 9) built in, C — condenser microphone (Fig. 6) with built-in preamplifier (Fig. 8), D — Holgate Ultrasonic Detector with microphone (d), E — leak detector (Fig. 5), F — Kuhl speaker (Fig. 6), and G — Battery-operated driver amplifier for an electrostatic loudspeaker (F) (Fig. 16). The condenser microphone, period meter, and portable oscilloscope make a versatile and portable field combination for studying ultrasonic signals. Scale is 10 cm.
Apparatus for Research on Animal Ultrasonic Signals

Abstract

Apparatus appropriate for field studies of ultrasonic signals (10 to 150 kHz) is described with reference to the types of displays of the sounds that they produce. Simple narrowband ultrasonic detectors (leak detectors), broadband ultrasonic detectors including Knowles microphones, and tuneable narrowband detectors are reviewed, and circuits for the construction of leak detectors and broadband detectors with amplifiers are presented. A circuit diagram for a zero-crossing period meter which provides an oscilloscope display of the frequency pattern through time of vocalizations is illustrated with comments about its use in studying ultrasonic (or other) signals. The characteristics of different ultrasonic equipment are compared (Table 2), and the limitations of each system discussed in terms of the acoustic data they make available for analysis. Stress is placed on equipment suitable for field research, and two instrumentation tape recorders suitable for recording sounds to 300 kHz are discussed, along with equipment, including circuits, for producing ultrasonic sounds under field or laboratory conditions.

(ultrasonic microphones, speakers, amplifiers, zero-crossing period meter, bats, rodents, insects, echolocation)

Introduction

Ultrasonic sounds play an important role in the lives of many mammals and insects (Sales and Pye, 1974). Most mammals can hear sounds above the upper frequency limits of human hearing, reflecting the fact that the range of human hearing can be considered deviant from that of most mammals that have been studied (Masterson et al., 1969). Ultrasonic communication signals, and biological sonar signals and their echoes all contribute to the causation of behaviour and hence to the evolution and present ecological conditions experienced by many species. Understanding the lives of many animals requires eavesdropping on the ultrasonic world in which they live, and observation of sounds not audible to humans requires special equipment to convert information conveyed by imperceptible energies to stimuli receivable by human senses.

The choice of a method for converting ultrasonic information used by animals into a display suitable for human detection depends upon the nature of the scientific questions being approached through observation of the ultrasonic signals. This is an important decision since acoustic information not recorded is lost to future analysis,
and because the cost of ultrasonic apparatus and the effort expended in observations depend upon the proportion of sound information to be retained for further study. It would be wasteful to use condenser microphones and a high frequency instrumentation tape recorder to determine the presence or absence of ultrasonic signals. Conversely, when the nature of the acoustic waveform must be known, then a simple system of narrowband ultrasonic sensors would destroy virtually all of the relevant information about signal structure.

Here we describe techniques for studying sounds with frequencies from 10 to at least 150 kHz (ultrasonic for our purposes) encompassing the range of the high frequency sounds used in the behaviour of most animals (Busnel, 1963; Sales and Pye, 1974). We hope to help the reader to choose apparatus appropriate to different scientific problems involving animal ultrasound, and to decide which aspects or features of the acoustic signal to observe. It may not be clear to scientists having little practical experience with acoustics research just what kinds of problems can be approached with which kinds of equipment. Technical advisors lacking first hand experience with the many difficulties associated with biological field research might benefit from looking at this report when advising researchers about apparatus and procedures. Many of the examples given here are drawn from our experience with studies of echolocation by bats, but they can be generalized to other animals and other situations.

Many of the devices we have described here are available commercially and our information about sources is accurate as of August 1978. Circuit diagrams for practical, working equipment suitable for packaging in small, rugged cases for field research are provided. Most of the equipment we describe can be operated from 9 volt transistor batteries (we recommend Mallory MN 1604 batteries or their equivalents) or from 1.5 volt "D" cells. Rechargeable batteries of the same voltage are also suitable and we have used solar-powered chargers when working at isolated field sites. We recommend that replacement batteries be carried into the field since many types of batteries available in the United States, Canada, and western Europe are not easily obtained in many other parts of the world. Readers will find it valuable to try to keep up with new developments in portable power technology, as novel, inexpensive and more efficient power sources often become available.

The circuits we have shown here can be built by "anyone" with experience using solid-state analog (linear) and digital integrated circuits. Critical aspects of design or construction are noted in the text, and identifying part numbers are given where the selection of components is important. With a little guidance we hope that most biologists can learn to assemble these circuits using the facilities available in the shops of many universities. The data sheets and application notes available from the manufacturers of particular integrated circuits generally contain enough information to analyse in detail the function of any of the components in the circuits we have presented.

We consider this a tutorial report and readers should consult general Physics textbooks for background information on acoustics and wave propagation. Specific information on acoustical apparatus and ultrasonics can be found in Sales and Pye (1974) and Griffin (1976). More sophisticated treatments of acoustical problems and measurements are available in Beranek (1949), Kinsler and Fry (1962), Broch (1971), and Peterson and Gross (1974). An excellent discussion of the nature of acoustic stimuli is provided by Geldard (1972).
Descriptions of Sounds

The Acoustic Features of Sounds

A sound is a series of rapid fluctuations in air pressure observed at a point past which the wavefront moves. There are several different features of sounds which can be measured and which must be specified for characterizing sounds as signals. Sounds have amplitudes corresponding to the size of the air pressure fluctuations around the average or resting air pressure of the atmosphere, and frequencies corresponding to the rate of occurrence of these fluctuations. Sounds generally consist of fluctuations occurring at certain frequencies (measured in Hertz, Hz, or kilohertz, kHz), and not at others, and some frequencies are represented more strongly than others in the acoustic waveform. Sounds of biological importance have durations measured in time, usually in seconds or milliseconds (ms), and within the total duration of the sound, the frequencies may change from one time to another.

To describe a sound one can simply use an oscillogram or graph of the sound pressure (loudness) changes in the signal as a function of time; this is the acoustic waveform (Fig. 1). The waveform is equivalent to a set of raw data, and it is usually more convenient to summarize the characteristics of the signal with some descriptive terms: duration, average (root-mean-square, RMS) or maximum (peak-to-peak) sound pressure, frequency ranges, and the nature of changes in frequency with time. The aim is to display the relevant features of the sound from the point of view of the scientist who usually hopes to approximate the point of view of the animal hearing and/or producing the sounds.

When documentation of the presence or absence of sound at known frequencies is all that is required, an event recorder driven by an ultrasonic detector provides an adequate set of data. This type of record could show, for example, when ultrasonically active animals are present near the detector, and would allow one to monitor the timing of the activity of some echolocating bats, or of ultrasonic emissions by rats.

When it is necessary to document the kinds of sounds used by animals in different situations, then the display must contain information about the identifying features of the sounds as well as when they occur. Where different animals are known to use widely separate amplitudes or frequencies, the event recorder driven by narrowband ultrasonic detectors appropriately tuned to different frequencies may also work. However, more often the signals which distinguish one animal from another, or the signals of one animal in different situations, overlap to some extent in amplitude and frequency characteristics. The signals must then be analysed for smaller differences in specific frequency components or for differences in the pattern of a) the strength of the signal at different frequencies (amplitude spectrum, Fig. 2), or b) the frequencies as a function of time (sound spectrograph, Fig. 3). To obtain displays of such features of sounds requires rather sophisticated but not necessarily expensive field apparatus for producing displays as the sounds occur ('period meter', see page 20), or a tape recorder or other storage device which allows recordings of sounds to be returned to the laboratory for more detailed analysis with, for example, a Kay Sound Spectrograph or a Fast Fourier Transform real time spectrum analyser.
Displaying Acoustic Features

The display of relevant features of sounds can consist of a picture or graph of the signal (Fig. 1), of the frequencies present and their amplitudes (Fig. 2), or their times of occurrence (Fig. 3), or it can be the value of a dial setting to obtain a reading on a meter. The display can also be an audible sound, rather than a visual pattern. One of the most useful instruments for studying animal ultrasonic sounds simply converts such signals into sounds audible to man. With such a device one can observe the animal's behaviour while listening for any emission of ultrasonic signals.

A more sophisticated instrument incorporating an audible display makes a sound whenever it detects an ultrasonic signal at a specific frequency, and not at other frequencies. With a calibrated dial for tuning the instrument to different frequencies, one can adjust the instrument to achieve the maximum audible signal, and by reading the dial determine the most prominent frequency in the animal's ultrasonic sounds. By noting the range of dial settings which yield any substantial audible sounds from the apparatus, it is possible to determine the frequency range of the signals (any audible frequency components may be identified by switching off the microphone and listening with your unaided ear). These pieces of information can often distinguish one type of sound from another, or one species of animal from another, and all the while the observer can watch the animals' behaviour (Sales and Pye, 1974).

It is obvious that the nature of the biological problems being investigated through observation of ultrasonic signals influences both the choice of acoustic features to be displayed and the mode of display. If on-the-spot correlation of behavioural observations with types of sounds is desired, the display of relevant acoustic features must be instantaneous and must not severely interfere with other types of simultaneous behavioural observations. Clearly, tape recording the sounds for subsequent analysis does not provide immediate information about the acoustic components of behaviour. However, it is possible to record the sounds while also videotaping or filming the behaviour as a means of establishing behavioural correlations with ultrasonic emissions. The recording and filming apparatus is expensive and may not be practical under extreme field conditions (e.g. at night in a rain forest in the rain).

The apparatus described below provides a variety of different auditory and visual displays of selected acoustic features of ultrasonic signals. In some cases, the displays are available immediately, while in others they can only be obtained after subsequent processing of the recorded data.

Ultrasonic Instruments

Basic Components

Apparatus for gathering information about ultrasonic signals consists of several distinct functional components (Fig. 4). All of these instruments functionally begin by transducing the ultrasonic acoustic event into an electrical signal by means of a microphone. Since microphones generally produce very weak electrical signals, the output of the microphone is amplified 100 to 1,000 times (+20 to +40 dB) to make it strong enough to activate an analysing device or to drive a tape recorder (Fig. 4).
Fig. 1 The waveform of a sonar sound used by a Mexican free-tailed bat, Tadarida brasiliensis.
The sensitivity of a microphone is not improved by amplifying the signal produced by the sound. The smallest detectable sound level ordinarily depends upon the electrical noise in the circuit comprising the microphone and the first stage of the amplifier. This electrical noise is amplified along with the signal from the sound. If the signal representing the sound is weaker than the electrical noise inherent in the circuit elements of the amplifier, it cannot be detected. The sensitivity of an acoustic detector is thus improved by lowering this electrical noise relative to the signal, not by amplifying both (Griffin, 1976; Pye, personal communication). The analysing device receives the signal from the microphone’s amplifier (or from a tape recorder) and processes whatever acoustic feature is of interest for display. For example, if the duration of the sound is the only feature of interest, the analyser, a counter (oscilloscope or chart or event recorder) would display the time interval between onset and offset of the signal. Intensity and frequency information about the ultrasonic signal would be destroyed by the analyser.

The display component consists of the specialized circuits required in an oscilloscope, an interval or frequency counter, and an audio amplifier to drive a loudspeaker or a chart recorder. Modern integrated-circuit technology makes it possible to construct circuits to process information about fairly complex features of ultrasonic signals without great bulk or expense; for example, most of the devices described here can be built for less than $100 U.S. each in parts. The assembly of these circuits is not very difficult or complex since the building-blocks provided by
integrated-circuit packages perform sophisticated operations and can be thought of as equivalent to the symbols in the block diagram.

**Simple Ultrasonic Detectors**

The simplest and most inexpensive apparatus for detecting the presence of ultrasonic signals consists of a crystal microphone as the transducer, an amplifier, and a loudspeaker or earphone with an associated audio amplifier (Fig. 5). Crystal microphones tuned to particular frequencies respond to a narrow range of frequencies around the tuned frequency. The unit (Fig. 5) uses a Massa sensor TR-89G as a transducer and while tuned to 40 kHz, will respond to sounds from roughly 30 to 50 kHz. The integrated circuit amplifies the microphone signal and the transistor drives the earphones. Transient elements in the sound at the crystal microphone are
heard as clicks by the listener, who does not hear the ultrasonic composition of the sound itself. Units of this design are sold commercially to detect the hissing sounds of gas leaking from lines and are referred to as "ultrasonic sniffers" or "leak detectors". Assembled units are currently available from the Science Workshops, Carleton University, Ottawa, Canada K1S 5B6.

The completed leak detector can be housed in an aluminum cylindrical case which can be conveniently held in one hand for field use. Although arrangement of circuit components in the case is not critical, care should be taken to avoid long lengths of wire between components. In building the unit some thought should be given to facilitation of the changing of batteries (9 volt transistor), and to waterproofing the closed case. We recommend the Massa sensor TR-89G because it is relatively water-resistant.

Leak detectors or tuneable ultrasonic sensors (see below) can be used to operate an event recorder via an amplifier (e.g. Fenton et al., 1973). This system, which can be operated from a 12 volt car battery, produces a trace indicating occurrences of ultrasonic signals near the detector and is ideal for studying the activity of some insectivorous bats. It can also be used to monitor ultrasonic activity from rodents or other animals. In our experience it is not practical to use a series of crystal microphones each tuned to a different frequency with the event recorder apparatus, and workers wishing to operate this type of sensing station are advised to use tuneable ultrasonic sensors instead of crystal microphones.

Leak detectors can detect many species of insectivorous bats at distances of up to 10 m when the bat and the transducer are aimed towards each other. When the transducer is not pointed towards the sound source, its sensitivity is reduced because the transducer is quite directional. Bats that use low-intensity orientation sounds, such as Neotropical frugivores, vampire bats, and some insectivorous bats, cannot be detected at distances beyond 1 m under the best of conditions. Insectivorous bats that use high-intensity echolocation sounds at frequencies outside of the tuning of the transducer (e.g. horseshoe bats, Rhinolophus) will not be detected unless they are very close to the transducer. The crystal transducer, albeit inexpensive and readily available from many electronics surplus dealers, is the limiting component in this system.

We recommend leak detectors for teaching purposes as they provide an inexpensive means of eavesdropping on the ultrasonic world of animals. Echolocating bats such as Myotis or Eptesicus pursuing prey in the field, or these bats echolocating in the laboratory, as well as rodents emitting ultrasonic cries, or the ultrasonic components of insect songs all provide good demonstrations of the often unsensed worlds in which many animals live and behave.
Fig. 5 A detailed schematic diagram of a simple ultrasonic detector, a "leak detector" employing a crystal transducer. This type of circuit is compact, has a low power drain, and can be conveniently packaged for field work. The detector is turned on by plugging in earphones or other system for display. Details of electrical components are in the Appendix.
Condenser microphones which respond to a broad range of ultrasonic frequencies (Kuhl et al., 1954) are expensive when purchased commercially and require some careful machining when produced in a workshop. However, these microphones are not restricted in response to a narrow range of frequencies (cf. leak detectors). The principles of the operation of condenser microphones are discussed by Sales and Pye (1974). The best commercially available ultrasonic condenser microphone, the Brüel and Kjær Model 4135 ("1/4 inch"), is very expensive and rather insensitive because its incorporated electronic components have a high noise level relative to the electronic signal produced by the sound. This is a precision laboratory microphone for acoustic measurement and calibration and we do not recommend it for use in the field. Brüel and Kjær periodically publish technical publications which are useful training manuals for learning about many aspects of acoustics, but the manuals say very little about how to work under most field situations.

Condenser transducers can function either to pick up or to generate sound. Figure 6 shows an exploded view of a cross-section of a typical condenser-type or electrostatic transducer. When the unit is used as a loudspeaker, the coaxial cable is connected from the transducer to a driver amplifier for generation of sound (see page 25). The

Fig. 6 A diagram showing the construction of a basic condenser transducer. In this configuration the unit can function as an electrostatic loudspeaker, while attached to a high-input-impedance preamplifier (Fig. 8) it can serve as a condenser microphone.
threaded attachment provided by the coaxial connector facilitates rigid mounting of
the loudspeaker.

When the transducer is used as a microphone, the metal shell is made substantially
longer to accommodate the first stages of the microphone amplifier, which must be
located very close to the transducer unit. The condenser microphone is a high
impedance signal source and shielding of a short transducer-to-amplifier connection
within the housing of the amplifier is essential for faithful reproduction of the acoustic
waveform in the electrical signal.

A comparison of the ultrasonic frequency responses (Fig. 7) of the condenser
microphone (Fig. 6) and the Bruel and Kjaer Model 4135 condenser microphone,
illustrates the relative sensitivity of the two instruments. The microphone amplifier
boosts the microphone output signal by as much as 20 to 40 dB above the levels
shown in Fig. 7. A detector using this or a similar condenser microphone will actually
respond to frequencies from 100 Hz to 150 kHz with about equal sensitivity, unless
the frequency response of the detector as a whole is additionally limited by
characteristics of its electronic circuits, a situation usually desirable if the frequency
range of the signals of interest is known and if lower frequency (audible to man)
interfering sounds are present. We recommend a detector frequency range of 10 to
150 kHz.

![Graph](image)

Fig. 7 The output frequency response of the transducer (Fig. 6) used as a microphone, compared with
that of a Bruel and Kjaer commercial ¼-inch condenser microphone. The decibels (dB) are
re 1 mV/dyn/cm², and we used 1.0 ms tone-bursts and the reciprocity method to perform these
calibrations.
Condenser microphones are used in many manufacturers' remote-control television tuner controls (e.g. RCA part no. 112343), and these units are relatively inexpensive with frequency responses from 10 to perhaps 90 kHz. If this frequency range is adequate for the scientific purposes intended, these television microphones can be used in association with circuits described below to assemble an adequate ultrasonic broadband detector. Commercially available ultrasonic apparatus includes a condenser microphone with the system (see below), and these microphone-amplifier units can be obtained separately for use in picking up sounds to drive other types of analysers or displays.

A new commercial condenser microphone available from Knowles Electronic Corp., Franklin Park, Illinois (see page 16), shows declining sensitivity at frequencies above 20 kHz, but is quite capable of picking up many bat sonar sounds from 10 m or more in the field. It is particularly convenient for field use because it is inexpensive, requires no polarizing voltage, and contains the impedance-matching first stage of the microphone amplifier as an integral part of the unit. A broadband ultrasonic detector using the Knowles microphone has been described by Andersen and Miller (1977), and an exceedingly simply system incorporating this transducer is described below.

MICROPHONE AMPLIFIERS

Figure 8 shows a diagram for an amplifier which can be used in conjunction with a condenser microphone and which is intended to be housed in the same case as the microphone itself. If the case is large enough, the batteries (both for the polarizing voltage and to drive the amplifier) can also be mounted inside. Otherwise, a multiconductor cable can serve to bring power from a battery pack or from some other component in the detector system to the amplifier. The amplifier requires a 9 volt transistor battery, and the microphone either a set of batteries (we usually use 8 Mallory M505 22.5 volt) or an electronic inverter to generate the 150 to 250 volt polarizing voltage for the condenser microphone.

In this circuit (Fig. 8), the two transistors (2N4403) match the impedance of the microphone to the impedance of subsequent electronic stages and provide some gain. The two integrated circuits further amplify the signal and lower the impedance of the circuit to drive a fairly long cable (we have used up to 50 m) from the microphone/amplifier case to the other components as required. Although this circuit amplifies the signal, its output (550 Mv peak-to-peak from a 40 kHz sine wave 85 dB SPL, linear with source 8 cm from the microphone) is still too weak to activate detector mechanisms or serve as the input to a tape recorder unless a high intensity ultrasonic source is very close to the microphone.

The signal from the amplifier (Fig. 8) can be further amplified (Fig. 9) to complete the task of boosting the size of the microphone signal to useful voltage levels. This particular circuit (Fig. 9) requires two 9 volt transistor batteries for operation. At this point in the amplification process, it is convenient to limit the sensitivity of the system for low frequency sounds if things such as speech will interfere with observing the animal’s ultrasonic signals. The input coupling capacitor (Fig. 9) can be chosen to help determine the low frequency response characteristics of the system. This capacitor should be 2200 pF, if substantial, irrelevant sounds are expected to be present in the frequency range of human speech. The size of the capacitor controls the
Fig. 8 Schematic diagram of a preamplifier with high-input-impedance for use with condenser microphones (e.g. Fig. 6). This circuit requires a 9 volt transistor battery for power, and a high voltage battery (180 to 250 volts) to polarize the microphone. If this circuit is to be used with an electret microphone, the polarization voltage is unnecessary. Details of electrical components are in the appendix; in this and subsequent Figures, "k" indicates kiloohms, and "M" megaohms.
Fig. 9 Schematic diagram of a line or ultrasonic amplifier to boost the output of a microphone amplifier (Fig. 8) for driving a recorder or an analysing circuit. The output of a Knowles microphone (see text) can be connected directly to the input of this amplifier. Details of electrical components are in the appendix.
extent to which ultrasonic frequencies are amplified over and above audio frequencies. By choosing the correct capacitors, you can prevent audio sounds in the environment from accidently triggering the detector. Using the 2200 pF capacitor gives a low-frequency cut-off of 5 kHz, while a capacitor of 0.05 µF gives a cut-off of 20 kHz.

**ANALYSIS AND DISPLAY**

The output of the line amplifier (Fig. 9) can be connected to an oscilloscope to view the signal waveform, to a tape recorder to store the signal, or to any one of several analysing and displaying components. For example, the amplified signal can be connected to an audio circuit to produce audible sounds when transient ultrasonic signals are picked up by the microphone. Most ultrasonic sounds are transients with abrupt beginnings and endings. When transient signals are amplified and used to drive a loudspeaker, one can hear the rapid onsets and terminations of what would otherwise be inaudible sounds. The *envelope* of the ultrasonic sound is what you are hearing, not the sound itself. The process of converting a high frequency signal into its lower frequency envelope is called *detection* in radio terminology and rectification and integration in modern electronics. Detection is a non-linear process and an efficient audio detector should incorporate a detector stage in its circuitry to convert the signal into its envelope. The simplest audio detectors do, however, rely upon the loudspeaker to produce envelope transients, which are audible to the unaided human ear. A small, portable audio driver and loudspeaker unit, the “microsonic amplifier”, is available from the Radio Shack (Tandy) Corporation, and is suitable to act as the audio display component in a detector system based on a condenser microphone. This microsonic amplifier is also powered by a 9 volt transistor battery.

A complete broadband ultrasonic detector could consist of the condenser microphone (Fig. 6), the microphone amplifier (Fig. 8), the line amplifier (Fig. 9), perhaps a circuit for filtering the ultrasonic band to the frequencies of interest, and an auditory display such as the Radio Shack microsonic amplifier. Basic circuits for high-pass and low-pass filters to restrict the displayed frequency band (where necessary) (Fig. 10) all employ LM310 integrated circuits powered by two 9 volt transistor batteries. Details of resistor and capacitor values for filters (Table 1) demonstrate how different cut-off frequencies can be achieved. By interposing the filter component into the instrument, particular ultrasonic frequency ranges can be selected for special attention. We recommend constructing the filters so that they can be turned on or off as required, allowing a broadband or filtered signal to be displayed. Parallel filter units can be designed and used together to yield separate displays of different frequency bands.

The circuits in Figs. 8, 9, and 10 are practical designs. If the use of two 9 volt batteries for power is objectionable, these circuits can be re-designed with the integrated circuits changed to components for operation from a single 9 volt battery. The necessary modifications are easily made with the aid of data and applications sheets from the manufacturers of the integrated circuits.

Short-duration ultrasonic signals can be made audible if they are rectified and integrated so that the envelope of the animals’ signal is used to drive a loudspeaker. A circuit suitable for obtaining the envelopes of ultrasonic signals (Fig. 11) uses the output of the line amplifier as input to the rectifier, the output of which drives the

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Radio Shack microsonic amplifier or some other portable audio circuit such as the output stage of Fig. 5.

This system produces auditory displays of signals and electrical signals for tape recording in the 10 to 150 kHz band (unless further filtering is incorporated), and it is similar to several commercially available sets of apparatus. The "Lincoln Laboratory Bat Detector", originally described by McCue and Bertolini (1964) has been modernized and is available from the Science Workshop, Carleton University. The circuits shown here (Figs. 8–10) are based on this apparatus.

QMC Instruments Ltd., 229 Mile End Road, London, E1-4AA, England, manufactures the QMC Bat Detector Model S100 which incorporates a broadband ultrasonic detector with electrical output for tape recording and an auditory display. The QMC instrument also operates as a tuneable narrowband detector for using audio displays to identify principal frequencies in ultrasonic sounds (see page 19).

Both the Lincoln and QMC instruments use condenser microphones as transducers, and the microphone and microphone amplifiers are available separately from the analysing and display subsystems. These are both superior quality condenser microphone systems, the most sensitive and broadband transducers currently available as assembled units. We recommend either for use as the "front end" of ultrasonic detecting and analysing systems employing oscilloscope displays of waveforms or of frequency structure (see page 20), and for recording sounds for later analysis in the laboratory.

The Knowles microphone which is useful for less precise or less sensitive applications than either the Carleton (Lincoln) or QMC microphones because it is relatively inexpensive, can be used to build a simple, broadband ultrasonic detector for many ultrasonic sounds (bat, rodent, or insect calls). When the Knowles microphone is coupled to two line amplifiers (Fig. 9), it forms the basis of a broadband detector similar in quality to the ultrasonic leak detector (Fig. 5). The

Table 1 Resistor (R) and capacitor (C)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>C1</th>
<th>R1</th>
<th>C2</th>
<th>R2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. High-pass filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 kHz</td>
<td>0.001</td>
<td>5.62</td>
<td>0.001</td>
<td>4.64</td>
<td>0.001</td>
</tr>
<tr>
<td>80 kHz</td>
<td>0.001</td>
<td>1.21</td>
<td>0.001</td>
<td>1.21</td>
<td>0.001</td>
</tr>
<tr>
<td>B. Low-pass filter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 kHz</td>
<td>3300</td>
<td>0.984</td>
<td>0.01</td>
<td>0.720</td>
<td>270</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R3</th>
<th>C4</th>
<th>R4</th>
<th>C5</th>
<th>R5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. High-pass filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 kHz</td>
<td>17.8</td>
<td>0.001</td>
<td>2.2</td>
<td>0.001</td>
</tr>
<tr>
<td>80 kHz</td>
<td>4.64</td>
<td>0.001</td>
<td>0.511</td>
<td>0.001</td>
</tr>
<tr>
<td>B. Low-pass filter</td>
<td></td>
<td></td>
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<tr>
<td>20 kHz</td>
<td>1.8</td>
<td>0.01</td>
<td>5.6</td>
<td>88</td>
</tr>
</tbody>
</table>

Resistance is in Kilohms and capacitance is in Microfarads, except where noted.
Fig. 10 Schematic diagrams for high-pass and low-pass filters (a and b, respectively) used to narrow the frequency band of interest for subsequent display. Values of resistors and capacitors for various frequency cut-offs are given in Table 1; further details of electrical components are in the appendix.
Fig. 11 Schematic diagram for a rectifier circuit for detecting the envelope of a short-duration ultrasonic sound and converting it into a signal to drive an audio circuit. Further details of electrical components are in the appendix.
Knowles detector has the advantage of not being restricted to 40 kHz by a crystal microphone. A broadband ultrasonic detector based on the Knowles microphone, can provide a fairly satisfactory replica of the ultrasonic waveform for tape recording or for analysis, but the detector is not as sensitive as either the narrow band crystal microphone or the Carleton or QMC units due to the relative insensitivity and declining high frequency response of the Knowles microphone. However, a useful partial analysis of bat sonar sounds can be readily accomplished with the Knowles microphone system (Andersen and Miller, 1977).

**Tuneable Narrowband Detectors**

Several instruments are available which provide auditory displays of selectable, narrow portions of the ultrasonic frequency band. These devices permit the identification of the approximate principal frequency and frequency range of ultrasonic sounds by listening to the display while tuning a calibrated dial. These units permit rough characterization of overall ultrasonic spectra in the field while observing other aspects of an animal’s behaviour. They are complete systems incorporating transducers, amplifiers, and analysis and audio display circuits. Some also provide an electrical representation of the ultrasonic signal, although one of these units, the Holgate Ultrasonic Detector, provides an insufficiently-amplified signal that is usually contaminated with high frequency interference. In many instances the types of sounds or species of animals can be determined with these tuneable detectors, given sufficient experience by the operator. One of these units, the QMC S100 also functions as a broadband ultrasonic detector (see page 16).

Tuneable detectors multiply (in an algebraic sense) the ultrasonic signal by an internally generated reference frequency, and filter the product to obtain the difference frequency. If the reference signal is tuned to within 10 kHz of the frequencies present in the ultrasonic signal, the difference frequency is audible. The tuneable narrowband detector displays this difference frequency as an audible sound. The process of translating the frequencies present in the ultrasonic sound down to audible frequencies is called “heterodyning”, and it is similar to the operation of a wave analyser or an AM radio receiver. The procedure (heterodyning) can be viewed as a means of shifting a high range of frequency to a low range. By tuning the reference frequency to different values across the ultrasonic band, the narrower audible band can be positioned for detection of any selected frequency in the ultrasonic band (Sales and Pye, 1974). Narrower frequency turning of the detector can be accomplished by using multiple heterodyning stages.

Tuneable narrowband detectors produce audible displays for long duration ultrasonic sounds, whereas broadband detectors, which render only the envelope of the ultrasonic signal into sound, only produce strong displays for short-duration ultrasonic signals. The QMC S100 is particularly useful because it separately provides both broadband and tuneable narrowband functions.

The Holgate Ultrasonic Detector is available from Holgate of Totton, Commercial Road, Totton, Hants, England. It is an older solid-state design requiring heavier batteries than the QMC unit (specifically Mallory M1603 or equivalent). It is wise to insist upon a copy of the Holgate detector circuit diagram as part of the purchase, since one is not usually provided with the instrument. The ultrasonic signal is available electrically from the Holgate, but the output is insufficiently amplified and
the signal is usually contaminated with high frequency interference (Griffin 1976). Furthermore, the information provided with the Holgate does not adequately describe its battery requirements, since not only a 9 volt battery (see above), but also batteries to provide the high voltage bias are required. Despite these shortcomings, the Holgate is a very useful instrument.

QMC Instruments has recently advertised another bat detector, the QMC Mini Bat Detector which is tuneable from 10 to 160 kHz but which does not provide a broadband signal output. This machine is less versatile than the Holgate or the QMC S100, and also much less expensive.

Tuneable narrowband detectors are helpful for identifying sounds and in some cases the species of animals producing sounds. After some experience with these instruments, an observer can learn to classify the signals and their principal frequency components. Broadband detectors are also useful for identifying some types of ultrasonic signals, but the best results with the largest number of signals when using an audible display, are achieved with tuneable detectors. Broadband detectors produce outputs which do differ in quality from short frequency modulated to long constant frequency ultrasonic sounds, but these differences are only general indicators and not as useful as the audible signal from a tuneable detector.

Tuneable detectors do not provide much information about the detailed frequency-time structure or frequency composition of ultrasonic waveforms, and more complete analyses of these features can be accomplished through a visual display of the organization of frequencies in time sequences.

Frequency-Time Displays, the Period Meter

Most animal sounds are best characterized by a visual display of their time-frequency structure, a sound spectrogram (Fig. 3). Apparatus for developing this type of display currently is bulky and expensive and not suited for field research. Improvements related to the use of integrated circuits and microprocessor computers for Fourier analysis of signals will probably result in relatively inexpensive, real-time sound spectrographic apparatus becoming available in the near future. However, now an abbreviated form of sound spectrogram derived from zero-crossing analysis of signals is the best approximation of this type of analysis available for field situations.

A practical, real-time transient signal analyser was described by Partridge (1967). This device counted the period between zero-crossings of signals in a manner similar to "period meters" of several types. Before displaying the period count this transient analyser converted the period into its reciprocal, frequency, and the resulting display showed the time structure of the principal harmonic in the input waveform as an oscilloscope tracing of frequency as a function of time. The Partridge circuit has been implemented using CMOS digital and linear integrated components for low power consumption, light weight, small size, and compatibility with operation from a 9 volt transistor battery. The resulting transient analyser is very suitable for field research requiring characterization of complex, temporally structured sounds. It is inexpensive to build and is compatible with small battery powered oscilloscopes such as the Non-Linear Systems Inc. Miniscope Model Ms–15 (Del Mar, California), which are relatively inexpensive and conveniently used in the field.

Figure 12 shows the circuits of the frequency display controller which forms the transient signal analyser (period meter) which produces on an oscilloscope a
time-frequency display. The ultrasonic frequency output of a condenser microphone system (transducer, microphone amplifier, and line amplifier) drives the display controller which prepares the signals for oscilloscope display of their reciprocal periods. The oscilloscope must have a D.C. coupled vertical input, and we have found a vertical sensitivity of 0.5 volts per division appropriate for the oscilloscope display. Horizontal settings (sweep rates) of 1, 2, 5, or 10 msec per division provide the most useful time bases for the oscilloscope display.

The sound spectrograph (Fig. 13) provides an example of the type of display produced by this system, albeit without the harmonics. Use of this instrumentation in the field readily allows the observer to distinguish between echolocation pulses produced by a cruising (Fig. 13A) or hunting (Fig. 13C) bat, as well as between different species of bats in some situations (Bell, personal communication). The instrument can also be used to observe time-frequency structure in speech sounds, bird songs, insect calls, and other types of acoustic signals. The principle disadvantage is that the period meter does not display harmonic structure. We recommend the period meter in conjunction with a broadband microphone system as the best system for field display of ultrasonic (or other) acoustic signals. We have also found it valuable for initial laboratory analysis of recordings made in the field, since it facilitates location of recorded signals which require more detailed analysis (for example by Kay Sound Spectrograph or Fourier analysis).

### Sound Recording and Study-Site Monitoring

Two commercially-available magnetic tape recorders are sufficiently portable for field recording of animal ultrasonic sounds. Both are very expensive (over $7000 U.S.) owing to the broad bandwidth and relatively high tape speeds required for direct recording of ultrasonic frequencies. The Store 4D recorder (in North America, Lockheed Electronics, Plainfield, New Jersey; in Europe, Racal-Thermionic Ltd., Hardley Industrial Estate, Hythe, Southampton S04 6ZH, England) is the most convenient to operate since it can use 7-in. standard plastic reels of ¼-in. audio or instrumentation grade mylar recording tape. Record level adjustments, calibration, and tape-speed changes are easily made with externally accessible switches. It is, however, a bit heavy (17 kg without batteries), but manageable by one person. The Pemtek Model 110A (Pemtek, Inc., Palo Alto, California) is lighter (under 10 kg with batteries), but uses only 4.75-in. metal reels of ¼-in. tape. Tape speed and level adjustments are made internally, making them difficult to manipulate in the field.

Of the two machines the Pemtek is more expensive and in some ways more convenient for field work, as it is rugged, easier to transport, and has its own attached battery pack. When using the Pemtek in the field, tape speed is preset at 76 or 152 cm per sec, and the recordings played back in the laboratory at reduced speeds on inexpensive quarter track audio tape decks. Both the Store 4D and the Pemtek record standard "hi-fi" configuration four-track tapes. However, tapes recorded on the Pemtek may require re-spooling from the special Pemtek reels to standard reels; the special Pemtek reels are expensive to purchase, but may be manufactured in a
machine shop somewhat less expensively. In the laboratory, the Store 4D is superior, and in the field it can operate from a standard 12 volt automobile battery, whereas the Pemtek requires an inverter to raise the power to about 30 volts. The convenience of the Store 4D controls, and several additional features which are standard on the machine, as well as the price, make it somewhat more attractive than the Pemtek to some users. Both machines are excellent instrumentation quality recorders/reproducers with frequency responses to 300 kHz (at 152 cm per sec). Other commercially available instrumentation machines that we have used are field portable only in the sense that they have handles for carrying.

The frequency structure of the principal harmonic in the ultrasonic signal can be processed and recorded in the field on an inexpensive, audio cassette recorder for subsequent display of many signal characteristics (Andersen and Miller, 1977). This alternative to recording the entire ultrasonic waveform on an instrumentation recorder preserves enough information about the signals for many biological investigations. In many instances, for example, the species of echolocating bat can be identified from the recorded data. This approach to the collection of data provides a low-cost practical way to monitor ultrasonic activity at several sites with inexpensive ultrasonic detectors (the Andersen-Miller design which uses the Knowles microphone), recording several channels simultaneously on an audio-quality cassette or reel-to-reel recorder. The recordings can provide useful information about which species of bats are active at different recording sites at different times of the night.

Data from many study sites in a region could even be radioed to a central receiving location using a variety of different kinds of relatively inexpensive transmitter/receiver systems.

Although much more expensive, one can directly record ultrasonic signals from up to four different sites on a Store 4D or Pemtek tape recorder, using a broadband detector system described above. These recordings would require many hours of time for analysis to convert the recordings into meaningful statements about animal activity and a computer facility would be useful for this task. The same information could be more economically gathered by stationing observers equipped with broadband detectors and period meters at four locations, although the signals would not, in this case, be recorded for further analysis.

These examples serve to illustrate the many possible ways of gathering data on ultrasonic sounds of animals, either by recording the sounds, recording abbreviated analyses of the sounds, or by making notes on the frequency-time characteristics of the sounds in the field. Without recording, we recommend the broadband detector with period meter and oscilloscope as the most effective way of studying animal

Fig. 12 Schematic diagram of a real-time zero-crossing transient signal analyser suitable for displaying time-frequency information about ultrasonic sounds. This circuit amplifies and clips input waveforms (CA3035 and CA3130A), marks the timing of zero-crossings in the waveform (SCL4528), counts the period of cycles (alternated by flipflops SCL4013A) into counters (SCL4040A) with respect to a clock frequency (SCL4025A and SCL4040A), and displays one completed count while the period of the next cycle is being determined (SCL4091A and SCL4016A) through a reciprocal-taking digital-to-analog converter (resistor network and 2N3638A). Thus, although the device begins as a period meter, its output to an oscilloscope is proportional to input frequency, not period. Further details of electrical components are in the appendix.
ultrasounds in the field. This system is also an excellent means of introducing students into the ultrasonic world of many animals. By simultaneously watching the display and reading observations into a cassette recorder, an observer can gather a great deal of information about the activity patterns of different kinds of bats (for example), as well as learning about the types of biosonar signals used by the bats under different circumstances. Ultrasonic detection systems can often be used profitably in conjunction with photomultiplier night-vision devices or low-light-level television cameras to observe behaviour and simultaneously document ultrasonic vocalizations. Once the scientist has some idea of the capabilities and limitations of his ultrasonic equipment, the limiting factors are ingenuity and interest.
Tape-recorded ultrasonic signals can be analysed by a variety of different techniques, depending upon the kind of information these sounds represent to the scientist. The simplest procedure is to reproduce the signals into the period meter to scan the frequency-time structures for patterns of interest or variations in these signals. Specific signals can then be singled out for analysis using a sound spectrograph, spectrum analyser, or digital computer programmed for any number of different signal analysis outputs. The tape of ultrasonic signals can be reproduced at 8, 16, or 32 times slower tape speeds to permit the observer to listen to the sounds for features of their structure.

The period meter provides a most efficient means of searching through tapes for signals of interest, whether the tapes are played at recorded or slowed tape speeds. Visual display of the signals in conjunction with audio display is a very effective means of analysis.

*Generating Ultrasonic Sounds*

Two important reasons for generating ultrasonic sounds are testing of microphones and other equipment, and observing and testing the responses of animals to specific sounds under field or laboratory conditions. The signals can come from an oscillator, function generator, noise generator, or pulse generator, or they could be sounds recorded from the animals themselves (Fenton *et al*., 1976).

The electrostatic transducer (Fig. 6) that serves as a condenser microphone can also be used as a loudspeaker when driven by an appropriate amplifier (Fig. 14), in this case for frequencies from 10 to 150 kHz. This circuit (Fig. 14) is most appropriate for use in the laboratory where a power line operated power supply is available to provide the 250 volts polarizing voltage. Many vacuum-tube devices contain a B+power supply that can provide the polarizing voltage if no specific high voltage supply is present.

Figure 15 shows the acoustic output of an electrostatic loudspeaker of the same design (Fig. 6) driven by the circuit (Fig. 14) with a 10 volt peak-to-peak input signal at the loudspeaker. The sounds coming from the speaker were measured using an uncovered Brüel and Kjaer Model 4135 condenser microphone 30 cm from the loudspeaker. These represent the maximum acoustic levels (Fig. 15) that can be obtained from the speaker and amplifier without waveform distortions of about 1 per cent of the total harmonic distortion.

The output curve of the loudspeaker (Fig. 15) rises by about 12 dB per octave to a peak around 100 kHz, a feature common to this type of electrostatic speaker. A modified electrostatic loudspeaker has been designed to produce a uniform or flat frequency response from 15 to 130 kHz (Machmerth *et al*., 1975) and this can be constructed in any well equipped machine shop. This type of loudspeaker may be ordered from the Science Workshop at Carleton University.
Fig. 14  Schematic diagram of a circuit for driving an electrostatic transducer to generate sounds at high frequencies. A well regulated electronic power supply is recommended for the 250 volts. The cable from the output to the transducer should be shielded and kept as short as possible. Further details of electronics are in the appendix.

Fig. 15  Acoustic output of an electrostatic transducer used as a loudspeaker (see page 25); decibels (dB) are re 1 dyn/cm² at 30 cm (peak-to-peak).
Fig. 16 Schematic diagram of a portable, battery operated driver amplifier for an electrostatic loudspeaker. Further details of electronic components are in the appendix.
Table 2  Summary of some characteristics of apparatus for studying ultrasonic signals, including: Broadband—electrical output of ultrasonic signal suitable for recording, complete analysis and display; Derived—electrical output of derived signal suitable for incomplete analysis and display; Display—audio, meter, visual; Batteries—ease of access; Frequency Identification—without accessories; Frequency Range of Microphone; Sensitivity—relative ability to detect signals; Cost—as of August 1978; Commercial—where units can be ordered. For further details see text.

<table>
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<tr>
<th>System</th>
<th>Broadband</th>
<th>Derived</th>
<th>Display</th>
<th>Batteries</th>
<th>Frequency Identification</th>
<th>Frequency Range in kHz</th>
<th>Sensitivity</th>
<th>Cost U.S. $</th>
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<td>850</td>
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<td>200</td>
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<td>fair</td>
<td>100</td>
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<td>yes</td>
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<td>fair</td>
<td>800</td>
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<td>no</td>
<td>10-100</td>
<td>fair</td>
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<td>1977)</td>
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<td>meter</td>
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<td>no</td>
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<td>audio²</td>
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<td>—¹⁴</td>
<td>ca600</td>
<td>Carleton²</td>
</tr>
</tbody>
</table>

¹With accessory such as earphones, piezoelectric transducer, or equivalent; ²Science Workshops, Carleton University, Ottawa, Canada K1S 5B6. Completed unit cost on a per order basis as actual cost assessed by unit. Workshop will sell components at cost for those who want to assemble their own; ³QMC Instruments Ltd., 229 Mile End Road, London E14AA, England; ⁴Also available from other outlets, but we strongly recommend the Massa TR-89G sensor; Broadband signal is weak and contaminated; ⁵Accompanying information does not mention batteries that provide polarizing voltage to the microphone; ⁶Holgate of Totton, Commercial Road, Totton, Hants, England; ⁷Spectrum somewhat distorted; ⁸Microphone with preamplifier and amplifier (2209 or 2606); ⁹Batteries vary as model of amplifier; ¹⁰frequency range determined by amplifier and microphone grid; ¹¹Bruel and Kjaer, DK-2850 NAERUM, Denmark; ¹²frequency-time structure on oscilloscope; ¹³Limited by microphone.

* = units compatible with period meter.
For generating ultrasonic signals under field conditions a battery operated loudspeaker driver is essential. A circuit operating from a 45 volt battery (Fig. 16) requires a polarizing voltage of 250 volts nominally, but the bias supply for a condenser microphone (Fig. 8) can also be used as a source for the loudspeaker. Both driver circuits (Fig. 14 and 16) and the transducer shown here (Fig. 6) or the uniform response transducer (Macmerth et al. 1975) have been thoroughly tested under a variety of laboratory and field conditions, and found to perform very well. They represent a good system for producing ultrasonic sound to test equipment or the responses of animals to high frequency sound.

Conclusion

A condensation of the performance features of the ultrasonic detecting and analysing devices described here (Table 2) should help the reader choose from among the available apparatus according to the specific needs of particular research projects. The most critical step in the study of ultrasonic acoustic behaviour of animals is the statement of the problem at the beginning, since assumptions and perspectives from this point influence subsequent work and thought, as well as the selection of appropriate equipment. A good idea may manifest itself in data with a minimum of equipment, while a poor idea may yield no useful information even with a great deal of expensive equipment. Good luck!

Acknowledgements

We are grateful to Patricia Brown, Mark Camp, Donald R. Griffin, W.A. Lavender, J. David Pye, and Mark Terk for their advice and assistance. The development of these circuits was supported by National Science Foundation Grant no. BMS 72092351-A01 to JAS, by the Science Workshops at Carleton University, and by National Research Council of Canada Operating and Equipment Grants to MBF.
Appendix: Electrical Components

1. All resistors can be ¼ watt 5 per cent unless otherwise indicated.
2. Coupling capacitors are rated for at least 50 to 100 volts except for those to microphones and loudspeakers and capacitors in the loudspeaker driver circuits which should all be rated for at least 400 volts.
3. CMOS digital logic and linear integrated circuits are available from National Semiconductor Corp., and inexpensive surplus units can be purchased from many electronics distributors, some of which advertise in popular electronics magazines.
5. External switches for turning power off and on should be either locking toggle switches or rotary types with round knobs to prevent accidental switching on of equipment during transport. We recommend removing batteries from the apparatus which is being stored, to prevent corrosion of battery holders and adjacent parts.
6. The Knowles microphone (Model BT-1759) can only be ordered in minimum lots of 100 units, although some units are currently available from J.A. Simmons. In future, with continuing demand, group orders of 100 units could be co-ordinated by interested researchers. The relative insensitivity and frequency-dependent response above 20 kHz renders these microphones most suitable for qualitative and some quantitative observations of ultrasonic signals greater than 0.01 Newtons per meter squared in sound pressure. Soldering leads to the Knowles microphone is somewhat delicate work requiring competent technical help.


