Detecting Bats with Ultrasonic Microphones

Understanding the effects of microphone variance and placement on detection rates

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1 INTRODUCTION

All microphones of a given type exhibit differences among individual sensors due to tolerances in their materials, dimensions, and construction. Even the most tightly specified precision ultrasonic sensors costing over 1,000 USD (without preamplifiers and recorders) have a sensitivity variance of ±2dB[1] which is equal to a 25% difference in the amplitude of a signal.

This paper quantifies the characteristics and normal variance among ultrasonic microphones in general and Wildlife Acoustics ultrasonic microphones in particular, and how these differences might affect the detection of bats. We also examine how placement of the microphones in relationship to where the bats are active is much more significant to detection rates.

Finally, we address the calibration of microphones, and why the task is intractable in practice. More importantly, we address how to best determine if a microphone is operating within normal variance.

We focus on two specific microphone sensors, the MEMS and the FG, both manufactured by Knowles Acoustics and used in the majority of bat detectors and recorders from many different vendors including Wildlife Acoustics. The principles outlined in this paper apply to other microphone types as well.

We do not address differences in the electronics, triggering algorithms, technology, and configuration parameters used by different bat detectors and recorders which can also affect detection rates. That being said, two detectors of the same type will generally differ only by a fraction of a decibel given the tolerances of electronic components, and a well-designed bat detector will be limited only by the limitations of the microphone.

2 MICROPHONE CHARACTERISTICS – A TUTORIAL OF TERMS

2.1 SENSITIVITY

Microphone sensitivity is a measure of the electrical output of the microphone sensor (volts) given a known sound pressure at a known frequency. For conventional acoustic microphones, a sound pressure of 1 Pascal (94dB SPL re 0dB = 20×10^{-6} Pascal) at 1 kHz is commonly used. There are numerous acoustic microphone calibrators on the market that produce such a signal for calibrating sound level meters, often with calibration data traceable to the National Institute of Standards and Technology (NIST) or other agencies. Unfortunately, there are no standards nor commercially available and traceable calibration equipment for ultrasonic microphones where frequencies of interest are between 20 kHz – 200 kHz for monitoring bats.

[1] G.R.A.S. 46BF Specifications, http://www.gras.dk/46bf.html

2.2 Frequency Response

Frequency response is the relative sensitivity of the microphone as the sensitivity changes through a range of frequencies. All microphones have variation in sensitivity at different frequencies. In other words, a microphone will be more sensitive at some frequencies and less sensitive at others.

2.3 Noise Floor

The noise floor of the microphone characterizes the frequency-dependent self-noise of the microphone, usually measured in dBV/√Hz. The denominator relates to the distribution of noise power through frequency bands where measurements in larger bands will have greater noise levels in proportion to the square root of the frequency bandwidth. This is because the power spectrum of the noise is distributed across the frequency bandwidth and power is proportional to the square of the amplitude. If we are interested in a wide range of frequencies, there will be more noise and lower signal-to-noise ratio when compared to focusing on a narrow range of frequencies. This principle becomes important in understanding why there is a lower noise floor when using larger FFT sizes for analysis and vice versa.

2.4 Signal to Noise Ratio (SNR)

The signal to noise ratio relates to the ratio between the frequency-dependent signal and the noise constrained by the signal bandwidth. Here, the signal would be the signal of interest received by the microphone such as the echolocation call of a bat. The noise will be the higher level of either the noise floor of the microphone, the noise floor of the recording electronics, or the noise floor of the ambient environment. For ultrasonic frequencies, the highest level of noise is usually the self-noise of the microphone. A signal that falls below the noise floor (or does not exceed it by a sufficient threshold) is undetectable. Thus, the SNR is the most important factor in understanding the detection rate of bats and relates to the microphone noise floor, sensitivity and frequency response.

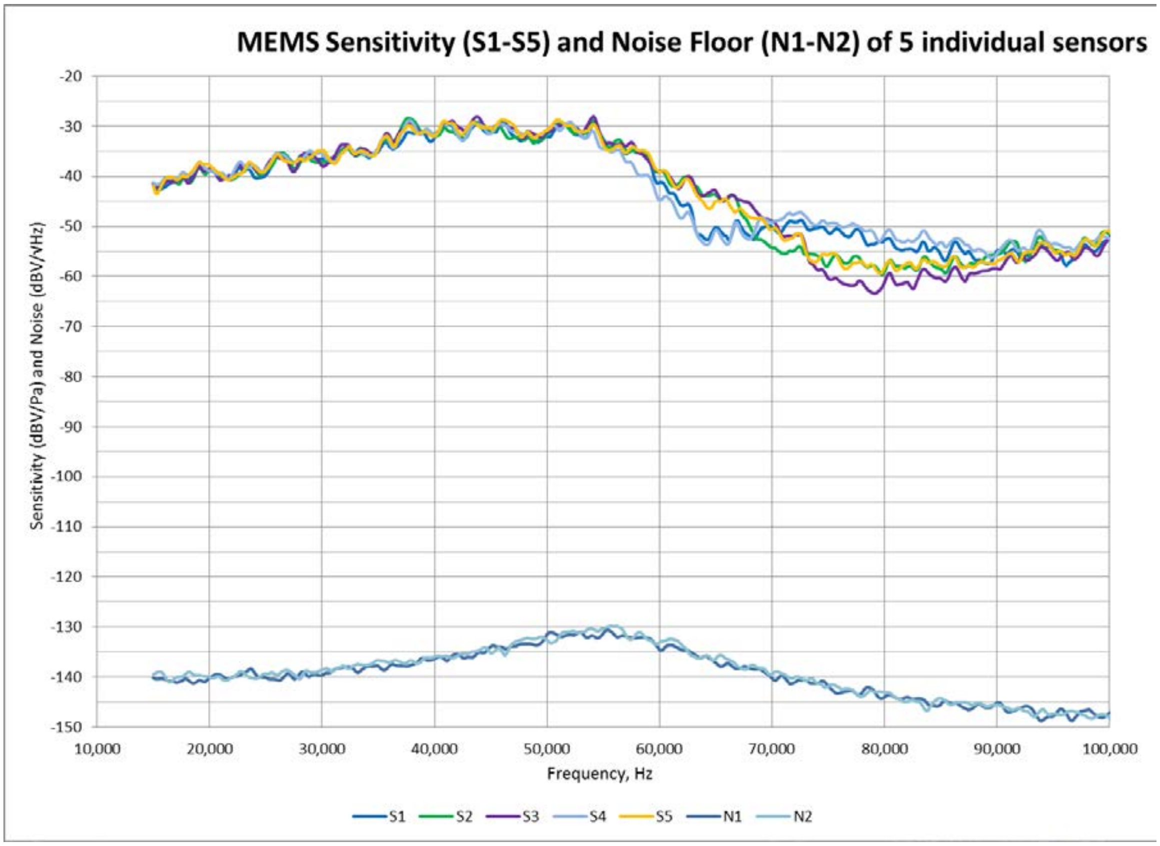
2.5 High Pass Filter (HPF)

A high pass filter is an electronic circuit (or digital algorithm) used to reduce unwanted low frequency noise. Bat detectors commonly use an analog high pass filter to attenuate low frequency sounds to improve the dynamic range available for recording the ultrasonic signals of bats.

3 Wildlife Acoustics Ultrasonic Microphone Characteristics

3.1 SMX-US, SMX-UT, and EM3 Microphone Characteristics

The Wildlife Acoustics SMX-US, SMX-UT and EM3 microphones are based on the Knowles SPM0404UD5 MEMS ultrasonic sensor. This sensor was discontinued by Knowles in 2012 and is no longer available. The characteristics of these microphones are inherited from this sensor. The figure below from data provided by Knowles shows typical sensitivity, frequency response and noise floor for several individual sensors (labeled S1 through S5 for sensitivity measurements and N1 through N2 for noise measurements). Wildlife Acoustics in-house testing further supports Knowles data.



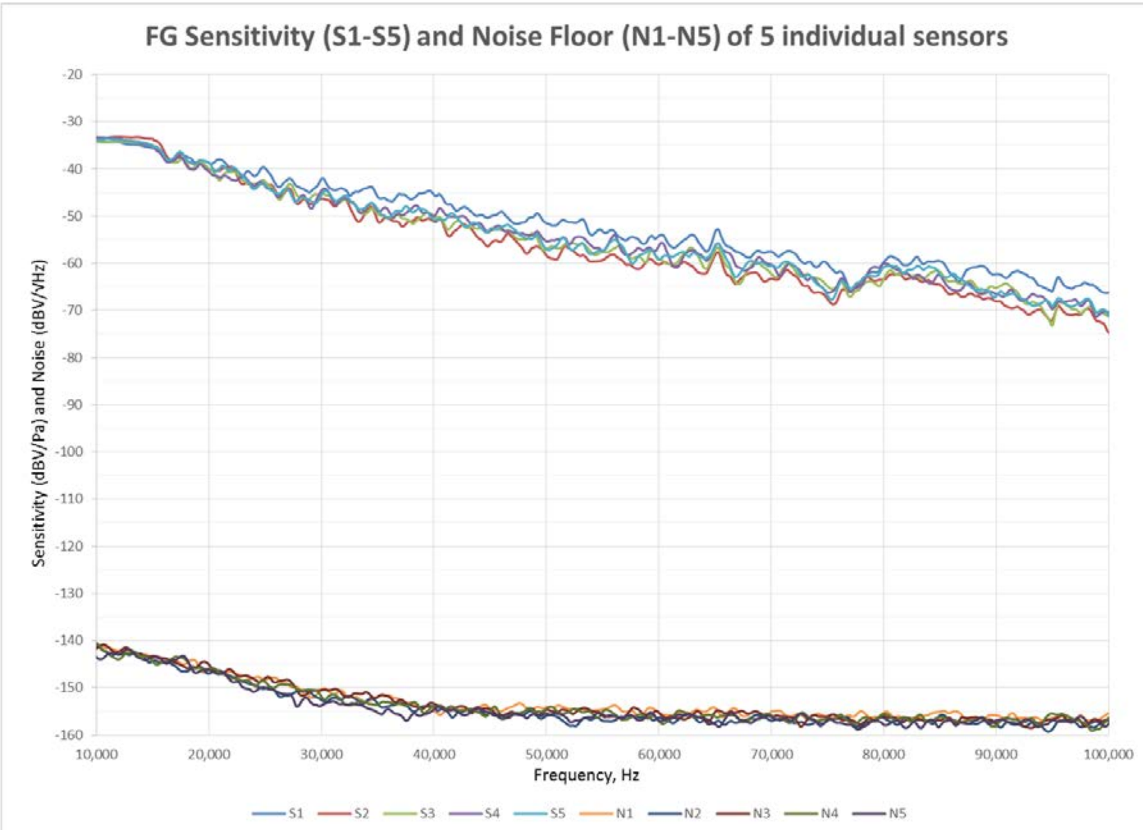
The MEMS sensor is specified to a variance of ±4dB and indeed all new SMX-US microphones have sensitivity and SNR within this range.

The MEMS sensor has an unusual frequency response with a very strong sensitivity (and noise) in the 40 – 60 kHz range and then dropping sharply to 20dB lower levels beyond 70 kHz. The SMX-UT and EM3 employ additional electronics to flatten the frequency response by amplifying the signal (and noise) above 70 kHz. Because the noise is also amplified, the signal to noise ratio remains unchanged.

The MEMS sensor can be destroyed by liquid water, so the SMX-US and SMX-UT microphone makes use of a weatherproofing system consisting of an acoustically transparent hydrophobic membrane and a military grade open foam windscreen. This weatherproofing when dry only attenuates ultrasound by 1-2dB. Humidity does not appear to cause damage to the MEMS as long as it is non-condensing. However, if the sensor is exposed to liquid water either by condensation or failure of the weatherproofing, the sensor typically loses significant sensitivity and becomes effectively unusable.

3.2 SM3-U1, SMZC, and Echo Meter Touch Microphone Characteristics

The SM3-U1, SMZC, and Echo Meter Touch microphones are based on the Knowles FG sensor. A 4-pole 8 kHz high-pass filter is used to filter out strong acoustic signals and 42dB of gain is added within the SM3-U1 electronics. Other than the intentional fall-off of sensitivity below 8 kHz due to the filter, the SM3-U1 microphone characteristics follow those of the underlying FG sensor. The figure below from data provided by Knowles illustrates the typical sensitivity, frequency response and noise floor. Wildlife Acoustics internal testing further supports Knowles data.



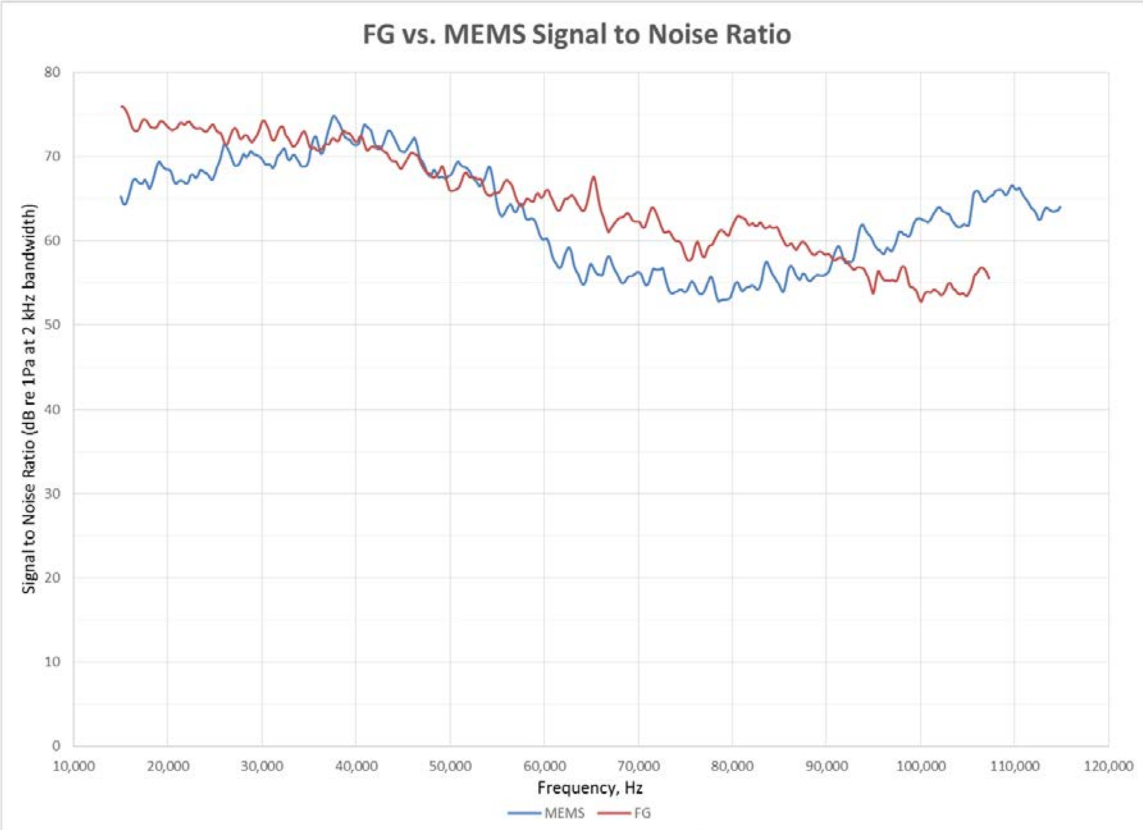
The Knowles FG is specified to ±3dB in the acoustic range and we find it consistent to ±4dB in the ultrasonic range consistent with Wildlife Acoustics testing.

The FG sensor has a much smoother frequency response and generally higher signal to noise ratio when compared to the MEMS sensor used in the SMX-US. The FG is also extremely resilient to moisture. Wildlife Acoustics has immersed FG microphones in water for extended periods of time, and they continue to operate like new when dried out. It may be possible that after several cycles like this some degradation could occur, and the SM3-U1 makes use of the additional weatherproofing methods used for the SMX-US to be conservative.

3.3 Comparison of SMX-US (MEMS) and SM3-U1 (FG) Microphone Signal to Noise Ratio

The chart below shows the average frequency-dependent signal to noise ratio of the SMX-US and SM3-U1 microphones based on the MEMS and FG sensors respectively. A 2 kHz bandwidth corresponds to 128-point FFT analysis of a recording made at 256 kHz sample rate, typical for the analysis of full spectrum bat echolocation calls.

Note that both the MEMS and FG sensors may vary by ±4dB.



4 IMPACT OF MICROPHONE VARIANCE ON DETECTION DISTANCE

The SMX-US microphone (MEMS sensor) and the SM3-U1 microphone (FG sensor) have a typical variance of ±4dB with respect to sensitivity and signal to noise ratio. This means that some normal microphones may be up to 8dB more sensitive than others. It is important to note that these differences may vary depending on frequency. For example, one microphone may be more sensitive at some frequencies and less sensitive at others compared to a second microphone of the same type.

A bat emits an echolocation call with varying sound pressure level through frequency and time. Different bats produce calls of different intensity, durations and frequencies. The calls propagate through air and will be attenuated by atmospheric absorption, spherical spreading of the pressure wave over distance, possible constructive and destructive interference from reflections, and ultimately cause the pressure wave to reach the microphone sensor. The bat's call may be directional in nature e.g. be stronger in the direction it is facing and weaker at other angles, and the geometry of the microphone sensor and assembly may also be directional in nature e.g. be stronger in some directions and weaker in others in a frequency-dependent way. When the echolocation call sound pressure wave finally reaches the microphone sensor, it is converted into an electrical voltage. The echolocation call will be detected only if the signal exceeds the noise by some threshold.

The wavelengths of echolocation calls in the 20 – 100 kHz range are between 3.4 and 17.1 millimeters. On such a small scale, even two side-by-side microphones with identical characteristics will receive the echolocation call differently unless they are spaced only millimeters apart which is not physically possible.

Detection distance is difficult to predict for all the reasons mentioned above. With that said, the difference in detection distance can be estimated given frequency and variance to mean signal to noise ratio.

The sound pressure level of the bat echolocation call as received at the microphone can be estimated by the following formula:

$$S_{mic} = S_{bat} - 3.3 * 10^{-5} * f * d + 20log_{10}(\frac{d_{ref}}{d})$$

Where S_{mic} is the sound pressure level in decibels received at the microphone; S_{bat} is the sound pressure level in decibels transmitted by the bat when measured at a distance d_{ref} from the bat in meters; f is the frequency in Hz, and d is the distance from the bat to the microphone in meters. The coefficient $-3.3*10^{-5}$ refers to the atmospheric absorption of ultrasound in air assuming 20^{o}C and 50% relative humidity.

Using this formula, and fixing S_{bat} = 94dB SPL with d_{ref} = 0.1 meters, and given the signal-to-noise ratio of the various microphones, the maximum detection distance can be estimated for different frequencies and degrees of microphone variance. (We choose 94dB SPL because this is the average output of the Wildlife Acoustics ultrasonic calibrator ±3dB in “chirp” mode. Many species of bat are louder than this, while others are quieter). The following tables illustrate the distance to the point where a signal is lost in the noise (i.e. 0dB SNR) at various frequencies and microphone variances. For all practical purposes, a useful signal for triggering and analysis will require some minimum SNR value above 0dB so the actual range would be less. The estimated detection distances are based on a 94dB SPL source signal noting that the actual amplitude of echolocation calls will depend on the species of bat and its orientation to the microphone.

MEMS ESTIMATED DETECTION DISTANCE OF 94dB SPL BAT (METERS)

	Sensitivity relative to average, dB								
Frequency, Hz	-4	-3	-2	-1	0	1	2	3	4
20,000	24.2	25.2	26.2	27.2	28.2	29.3	30.3	31.4	32.5
30,000	19.6	20.3	21.0	21.7	22.5	23.2	23.9	24.7	25.4
40,000	17.8	18.3	18.9	19.5	20.0	20.6	21.2	21.8	22.3
50,000	13.4	13.9	14.3	14.7	15.2	15.6	16.1	16.6	17.0
60,000	8.6	8.9	9.3	9.6	10.0	10.3	10.7	11.0	11.4
70,000	6.6	6.9	7.2	7.5	7.8	8.1	8.4	8.7	9.0
80,000	5.9	6.1	6.3	6.6	6.8	7.1	7.4	7.6	7.9
90,000	6.0	6.2	6.4	6.7	6.9	7.1	7.4	7.6	7.8
100,000	6.7	6.9	7.1	7.4	7.6	7.8	8.0	8.3	8.5

FG ESTIMATED DETECTION DISTANCE OF 94dB SPL BAT (METERS)

Sensitivity relative to average, dB

Frequency, Hz	-4	-3	-2	-1	0	1	2	3	4
20,000	30.0	31.1	32.1	33.2	34.3	35.4	36.5	37.6	38.8
30,000	22.6	23.3	24.1	24.8	25.6	26.3	27.1	27.8	28.6
40,000	17.5	18.1	18.6	19.2	19.8	20.3	20.9	21.5	22.1
50,000	12.4	12.8	13.2	13.6	14.1	14.5	15.0	15.4	15.9
60,000	10.7	11.0	11.4	11.7	12.1	12.5	12.9	13.2	13.6
70,000	8.5	8.8	9.1	9.4	9.7	10.0	10.3	10.7	11.0
80,000	7.9	8.2	8.5	8.7	9.0	9.3	9.6	9.9	10.1
90,000	6.2	6.4	6.7	6.9	7.1	7.4	7.6	7.9	8.1
100,000	4.9	5.1	5.3	5.5	5.7	5.9	6.1	6.3	6.5

As the frequency of interest increases, the dominant contributor to detection distance is the atmospheric absorption of ultrasonic signals and the change in detection distance becomes less significant between more or less sensitive microphones. For example, at 40 kHz there is a 4.5 meter (28%) difference in detection distance from the most sensitive to the least sensitive MEMS microphone, and this drops to 2.8 meters (25%) at 60 kHz (see MEMS table above).

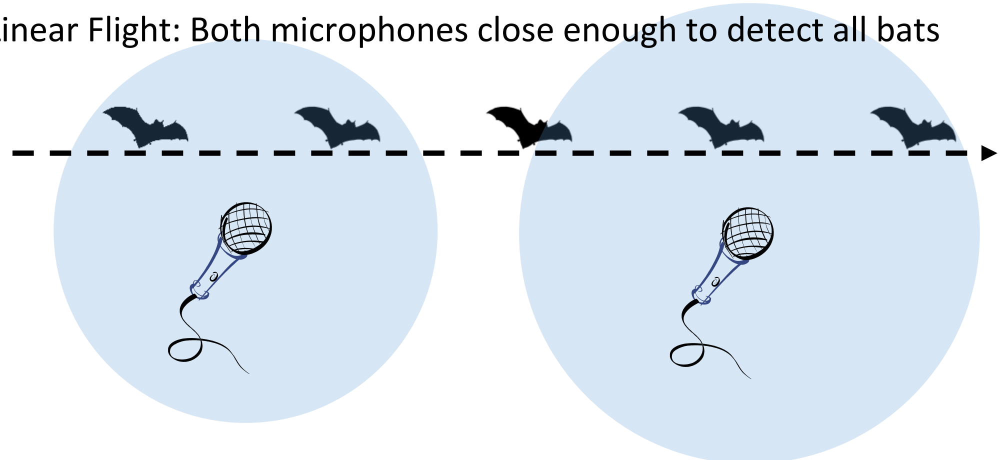
Also note that the source intensity of the bat echolocation call may vary significantly depending on the species of bat and its orientation (e.g. facing towards or away from the microphone). Or put another way, like microphones, individual bats will exhibit differences due to tolerances in their materials, dimensions, and construction.

5 IMPACT OF DETECTION DISTANCE ON DETECTION RATE

The relationship between detection distance and detection rate, or the number of bats recorded, depends entirely on microphone placement relative to the bats.

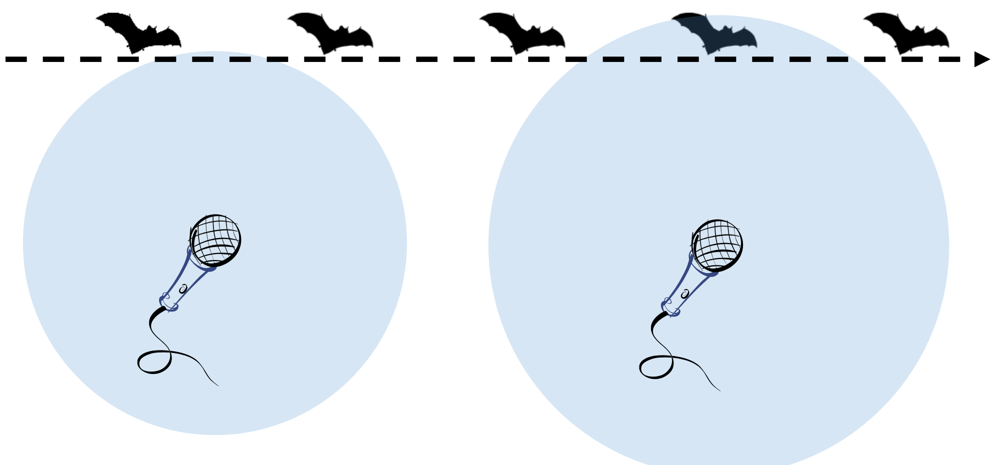
Consider the scenario of a linear flight path, for example along the top of a hedgerow, or through an opening in a roost. And suppose to make calculations simpler, the bat produces 40 kHz echolocation pulses with 94dB SPL at the source measured 10 cm from its mouth (consistent with the tables above). Let's also assume that we need only 0 dB SNR (which is unrealistically optimistic). If any two Wildlife Acoustics microphones are placed less than 17 m from the linear flight path, then both microphones should successfully record the bat even if one is -4 dB and the other is +4 dB nominal. The more sensitive microphone might cause a recording trigger to happen before the less sensitive microphone as the bat flies into range, but both bats should be recorded and detection rates should be comparable.

Linear Flight: Both microphones close enough to detect all bats



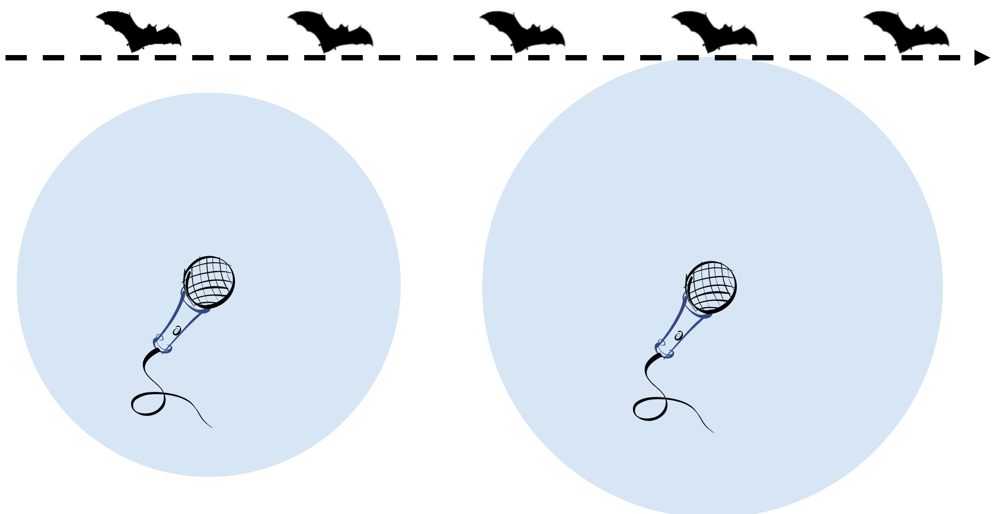
On the other hand, suppose the microphones are instead placed 18 m from the linear flight path. Now, the bats would be just out of range of the -4 dB microphone but still detected by the +4 dB microphone. In this scenario, one microphone would detect all the bats while the other would detect none. And the only difference was a change of microphone position by only one meter!

Linear Flight: One microphone detects all, one detects none



If the microphones are positioned just a little further away, neither would detect any bats. The point is that detection rates of even the most sensitive microphone can vary significantly depending on microphone placement. Without knowing where the microphone is in relationship to the bats makes it impossible to compare bat activity levels based on detection rates.

Linear Flight: Both microphones too far to detect bats



The above linear flight examples also apply in three dimensions to bats flying at some height. If the majority of bats are flying at some minimum distance above the ground, detection rates can be affected significantly by the height of the microphones. Even the most sensitive microphone may fail to detect bats if they are flying just out of range, while the least sensitive microphone may detect the majority of the bats if placed sufficiently high off the ground.

On another extreme, suppose there are bats flying at randomly distributed positions and heights over an open field with microphones placed together near the ground. An over simplification would be to consider the volume of habitat sampled. The ratio of volumes is proportional to the ratio of the cube of the radii. The difference in detection volume of a 40 kHz 94 dB SPL signal between a +4dB and a -4dB MEMS microphone would be proportional to $17.8^3/22.3^3 = 51\%$. However, it is not that simple. Imagine that region between the two concentric hemispheres. While it is true that a bat found in this region will only be detected by the more sensitive microphone, what is the probability that the bat would not also pass through the smaller hemisphere as it moved causing it to then be detected by the other microphone? Certainly most of the bats will more likely pass through the inner hemisphere if they also pass through the outer hemisphere. If the bats all flew perfectly straight at a constant altitude, the less sensitive microphone might pick up 64% compared to the more sensitive microphone (closer to a square function than a cubic function). And the variability of flight increases the chance for the bat to stray into range of the less sensitive microphone reducing the difference in detection rates further.

These examples are over simplifications, and actual distances would be reduced given that some minimum threshold of SNR above 0dB would be required for detection and analysis. The important thing to realize is that the movements and locations of bats, and thus the placement of microphones, has a much stronger effect on detection rates than the normal variance of the individual sensors. To maximize detection rates, the microphones should be placed as close to where the bats will be flying. This will ultimately make a much bigger difference in detection rates than any normal variation found in the microphones.

6 QUALIFYING MICROPHONES

Individual microphones have natural variance resulting in different detection distances for bats as discussed above. Detection rates may be difficult to predict without understanding the geometry of the microphone placement relative to bat activity. But if these relationships can be understood and modeled, it would be useful to know where an individual microphone lies within its range of normal variance.

Unfortunately, this is exceedingly difficult to accomplish with ultrasonic microphones. The wavelengths of interest between 20 kHz and 100 kHz are between 17.0 and 3.4 millimeters respectively. Reflections at half wavelength reflections can cause destructive interference, so changes of a quarter wavelength or between 1 and 4 millimeters can have an impact on how sounds can be received and measured. There are also no commercially available and traceable reference standards for ultrasonic transducers like there are for acoustic transducers. Microphones will also respond differently to near-field and far-field stimuli. If the test signal source is close to the microphone, the pressure wave arriving at the microphone is more spherical and will cause different kinds of interference as the wave interacts with the microphone housing when compared to the more planer pressure wave from a more distant signal source. Since bats are recorded at a distance, far-field test signals are critical, but also much more difficult to control without a large anechoic chamber and precision fixtures.

Without an anechoic chamber, the measurement error can easily be in the range of ±6dB which is more than the ±4dB variance in the microphones themselves. It is therefore impractical to expect that any easy method could be devised to determine if a microphone is more or less sensitive than average.

The Wildlife Acoustics calibrator in “calibrate mode” is useful to verify that a microphone is good or bad, but it is not useful for qualifying a microphone as being more or less sensitive within normal variance due to measurement error.

On the other hand, the calibrator can be used as a proxy for a 40 kHz ~94dB SPL bat when used in “chirp” mode. A large anechoic chamber is still required, but this can effectively be found outside in a field. An open field has only the ground as a potential source of reflection, but otherwise being open in all other dimensions allows sound to propagate without interference. Given that we do not expect a 40 kHz signal to be detected after 24 meters, the field should be larger than a 48 meter diameter circle. Placing the microphone 12 meters from the center guarantees that any reflection would have to make at least a 24 meter round-trip from the microphone to the edge of the field and back again. Then the calibrator can be positioned at the center of the field and moved to different test positions further away from the microphone until the calibrator signal is no longer detected (e.g. visible on a spectrogram in an un-triggered recording or strong enough to cause a trigger). This technique allows for the relative detection distance of one microphone to be compared against another, at least for a 40 kHz bat at ~94dB SPL aimed directly at the microphone. Note that the calibrator itself is directional and it is possible to see 10dB loss if the calibrator is slightly off of center, so you might try slowly altering the angle of the chirper slightly to try to find the sweet spot.

7 CONCLUSIONS

Variance in microphone sensitivity is an unavoidable reality. There are sensors available that would improve upon the variance somewhat, but such sensors are more than an order of magnitude more expensive and still have a variance of ±2dB. All microphones used in today's commercially available bat detectors have a variance of ±4dB as most of these bat detectors use either the Knowles FG or MEMS microphone sensors.

While it is true that microphone variance can affect the detection rate of bats, it is important to realize that microphone placement relative to the bats has a much more significant impact. Even the most sensitive microphone may fail to detect bats if it is placed just outside of range. Without knowing the position of the bats relative to the microphone, it would be impossible to draw any conclusions on relative bat activity based on detection rates.

8 ACKNOWLEDGEMENTS

I would like to thank Greg Falxa, Paul Howden-Leach and Lynn Robbins for their input and suggestions.

APPENDIX A: DETECTION DISTANCE TABLES

The following tables show approximate detection distances at various frequencies for the average MEMS (first table) or FG (second table) sensor relative to a 94 dB SPL source (measured at 10 cm) at 20˚C and 50% R.H. with relative SNR adjustments from -30 to +30 dB relative to 0 dB SNR. This table can be used to estimate detection distances of bats based on actual output SPL levels of the bat and minimum desired Signal to Noise Ratios in addition to microphone variance.

For example, suppose we want to determine the typical detection distance for a bat with 120 dB SPL output (+26 dB relative to the 94 dB SPL reference), with a minimum of 12 dB SNR (-12 dB relative to 0 dB SNR), and minimum microphone sensitivity (-4 dB relative to an average microphone). We would look for the rows corresponding to +10 dB (+26 – 12 – 4). For a 50 kHz signal detected by a MEMS sensor, this would be 19.8 meters (first table, +10 dB row, 50 kHz column).

Detection distance at 0dB SNR for mean MEMS sensor (meters)

dB relative to 94dB SPL source signal at 10cm, 20˚C, 50% R.H.	Frequency, Hz: 20,000	30,000	40,000	50,000	60,000	70,000	80,000	90,000	100,000
-30	5.2	5.1	5.7	4.0	2.0	1.4	1.2	1.4	2.0
-29	5.6	5.5	6.0	4.3	2.1	1.5	1.3	1.6	2.2
-28	6.1	5.9	6.4	4.6	2.3	1.6	1.4	1.7	2.3
-27	6.6	6.3	6.8	4.9	2.5	1.8	1.6	1.8	2.4
-26	7.1	6.8	7.2	5.2	2.7	1.9	1.7	1.9	2.6
-25	7.6	7.2	7.5	5.5	2.9	2.0	1.8	2.1	2.7
-24	8.2	7.7	8.0	5.8	3.1	2.2	2.0	2.2	2.9
-23	8.8	8.2	8.4	6.1	3.3	2.4	2.1	2.3	3.0
-22	9.4	8.6	8.8	6.4	3.5	2.5	2.2	2.5	3.2
-21	10.0	9.2	9.2	6.8	3.7	2.7	2.4	2.6	3.4
-20	10.7	9.7	9.7	7.1	4.0	2.9	2.6	2.8	3.5
-19	11.4	10.2	10.1	7.5	4.2	3.1	2.7	3.0	3.7
-18	12.1	10.8	10.6	7.8	4.5	3.3	2.9	3.1	3.9
-17	12.9	11.3	11.1	8.2	4.7	3.5	3.1	3.3	4.1
-16	13.6	11.9	11.6	8.5	5.0	3.7	3.3	3.5	4.3
-15	14.4	12.5	12.0	8.9	5.2	3.9	3.4	3.7	4.5
-14	15.2	13.1	12.5	9.3	5.5	4.1	3.6	3.9	4.6
-13	16.0	13.7	13.0	9.7	5.8	4.3	3.8	4.1	4.8
-12	16.9	14.3	13.5	10.1	6.1	4.6	4.0	4.3	5.0
-11	17.7	14.9	14.0	10.5	6.4	4.8	4.3	4.5	5.2
-10	18.6	15.6	14.6	10.9	6.7	5.1	4.5	4.7	5.4
-9	19.5	16.2	15.1	11.3	7.0	5.3	4.7	4.9	5.6
-8	20.4	16.9	15.6	11.7	7.3	5.6	4.9	5.1	5.8
-7	21.3	17.6	16.2	12.1	7.6	5.8	5.1	5.3	6.1
-6	22.3	18.2	16.7	12.6	8.0	6.1	5.4	5.5	6.3
-5	23.2	18.9	17.2	13.0	8.3	6.4	5.6	5.7	6.5
-4	24.2	19.6	17.8	13.4	8.6	6.6	5.9	6.0	6.7
-3	25.2	20.3	18.3	13.9	8.9	6.9	6.1	6.2	6.9
-2	26.2	21.0	18.9	14.3	9.3	7.2	6.3	6.4	7.1
-1	27.2	21.7	19.5	14.7	9.6	7.5	6.6	6.7	7.4
0	28.2	22.5	20.0	15.2	10.0	7.8	6.8	6.9	7.6
1	29.3	23.2	20.6	15.6	10.3	8.1	7.1	7.1	7.8
2	30.3	23.9	21.2	16.1	10.7	8.4	7.4	7.4	8.0
3	31.4	24.7	21.8	16.6	11.0	8.7	7.6	7.6	8.3
4	32.5	25.4	22.3	17.0	11.4	9.0	7.9	7.8	8.5
5	33.5	26.2	22.9	17.5	11.8	9.3	8.2	8.1	8.7
6	34.6	26.9	23.5	18.0	12.1	9.6	8.4	8.3	9.0
7	35.7	27.7	24.1	18.4	12.5	9.9	8.7	8.6	9.2
8	36.8	28.5	24.7	18.9	12.9	10.2	9.0	8.8	9.4
9	38.0	29.2	25.3	19.4	13.3	10.5	9.3	9.1	9.7
10	39.1	30.0	25.9	19.8	13.7	10.8	9.5	9.4	9.9
11	40.2	30.8	26.5	20.3	14.0	11.2	9.8	9.6	10.1
12	41.4	31.6	27.1	20.8	14.4	11.5	10.1	9.9	10.4
13	42.5	32.4	27.7	21.3	14.8	11.8	10.4	10.1	10.6
14	43.7	33.2	28.4	21.8	15.2	12.1	10.7	10.4	10.9
15	44.9	34.0	29.0	22.3	15.6	12.5	11.0	10.7	11.1
16	46.0	34.8	29.6	22.8	16.0	12.8	11.3	10.9	11.4
17	47.2	35.6	30.2	23.3	16.4	13.1	11.6	11.2	11.6
18	48.4	36.4	30.8	23.7	16.8	13.5	11.9	11.5	11.9
19	49.6	37.2	31.5	24.2	17.2	13.8	12.2	11.7	12.1
20	50.8	38.0	32.1	24.7	17.6	14.2	12.4	12.0	12.4
21	52.0	38.9	32.7	25.2	18.0	14.5	12.7	12.3	12.6
22	53.2	39.7	33.3	25.7	18.4	14.9	13.1	12.5	12.9
23	54.4	40.5	34.0	26.3	18.8	15.2	13.4	12.8	13.1
24	55.7	41.3	34.6	26.8	19.2	15.5	13.7	13.1	13.4
25	56.9	42.2	35.3	27.3	19.6	15.9	14.0	13.4	13.6
26	58.1	43.0	35.9	27.8	20.0	16.2	14.3	13.6	13.9
27	59.4	43.9	36.5	28.3	20.5	16.6	14.6	13.9	14.1
28	60.6	44.7	37.2	28.8	20.9	17.0	14.9	14.2	14.4
29	61.8	45.5	37.8	29.3	21.3	17.3	15.2	14.5	14.6
30	63.1	46.4	38.5	29.8	21.7	17.7	15.5	14.7	14.9

Detection distance at 0dB SNR for mean FG sensor (meters)									
	Frequency, Hz								
dB relative to 94dB SPL source signal at 10cm, 20˚C, 50% R.H.	20,000	30,000	40,000	50,000	60,000	70,000	80,000	90,000	100,000
-30	8.0	6.9	5.5	3.4	3.1	2.3	2.3	1.6	1.1
-29	8.6	7.3	5.8	3.7	3.3	2.4	2.4	1.7	1.2
-28	9.2	7.8	6.2	3.9	3.5	2.6	2.6	1.8	1.3
-27	9.9	8.3	6.6	4.2	3.7	2.8	2.7	1.9	1.4
-26	10.5	8.7	7.0	4.4	3.9	3.0	2.9	2.1	1.5
-25	11.2	9.3	7.3	4.7	4.2	3.2	3.1	2.2	1.6
-24	11.9	9.8	7.8	5.0	4.4	3.4	3.3	2.4	1.7
-23	12.6	10.3	8.2	5.3	4.7	3.6	3.5	2.5	1.8
-22	13.4	10.9	8.6	5.6	4.9	3.8	3.7	2.7	1.9
-21	14.2	11.4	9.0	5.9	5.2	4.0	3.9	2.8	2.0
-20	15.0	12.0	9.5	6.3	5.5	4.2	4.1	3.0	2.2
-19	15.8	12.6	9.9	6.6	5.8	4.4	4.3	3.2	2.3
-18	16.6	13.2	10.4	6.9	6.1	4.7	4.5	3.3	2.5
-17	17.5	13.8	10.8	7.3	6.4	4.9	4.7	3.5	2.6
-16	18.3	14.4	11.3	7.6	6.7	5.2	4.9	3.7	2.8
-15	19.2	15.1	11.8	8.0	7.0	5.4	5.2	3.9	2.9
-14	20.1	15.7	12.3	8.4	7.3	5.7	5.4	4.1	3.1
-13	21.0	16.4	12.8	8.7	7.6	5.9	5.6	4.3	3.2
-12	22.0	17.0	13.3	9.1	7.9	6.2	5.9	4.5	3.4
-11	22.9	17.7	13.8	9.5	8.2	6.5	6.1	4.7	3.6
-10	23.9	18.4	14.3	9.9	8.6	6.8	6.4	4.9	3.8
-9	24.9	19.1	14.8	10.3	8.9	7.0	6.6	5.1	3.9
-8	25.9	19.8	15.4	10.7	9.3	7.3	6.9	5.3	4.1
-7	26.9	20.5	15.9	11.1	9.6	7.6	7.1	5.5	4.3
-6	27.9	21.2	16.4	11.5	9.9	7.9	7.4	5.8	4.5
-5	29.0	21.9	17.0	11.9	10.3	8.2	7.7	6.0	4.7
-4	30.0	22.6	17.5	12.4	10.7	8.5	7.9	6.2	4.9
-3	31.1	23.3	18.1	12.8	11.0	8.8	8.2	6.4	5.1
-2	32.1	24.1	18.6	13.2	11.4	9.1	8.5	6.7	5.3
-1	33.2	24.8	19.2	13.6	11.7	9.4	8.7	6.9	5.5
0	34.3	25.6	19.8	14.1	12.1	9.7	9.0	7.1	5.7
1	35.4	26.3	20.3	14.5	12.5	10.0	9.3	7.4	5.9
2	36.5	27.1	20.9	15.0	12.9	10.3	9.6	7.6	6.1
3	37.6	27.8	21.5	15.4	13.2	10.7	9.9	7.9	6.3
4	38.8	28.6	22.1	15.9	13.6	11.0	10.1	8.1	6.5
5	39.9	29.4	22.6	16.3	14.0	11.3	10.4	8.4	6.7
6	41.0	30.2	23.2	16.8	14.4	11.6	10.7	8.6	7.0
7	42.2	31.0	23.8	17.3	14.8	12.0	11.0	8.9	7.2
8	43.3	31.7	24.4	17.7	15.2	12.3	11.3	9.1	7.4
9	44.5	32.5	25.0	18.2	15.6	12.6	11.6	9.4	7.6
10	45.7	33.3	25.6	18.7	15.9	12.9	11.9	9.6	7.9
11	46.9	34.1	26.2	19.1	16.3	13.3	12.2	9.9	8.1
12	48.0	34.9	26.8	19.6	16.7	13.6	12.5	10.2	8.3
13	49.2	35.8	27.4	20.1	17.1	14.0	12.8	10.4	8.5
14	50.4	36.6	28.0	20.6	17.5	14.3	13.1	10.7	8.8
15	51.6	37.4	28.7	21.1	18.0	14.6	13.4	10.9	9.0
16	52.8	38.2	29.3	21.5	18.4	15.0	13.7	11.2	9.2
17	54.1	39.0	29.9	22.0	18.8	15.3	14.0	11.5	9.5
18	55.3	39.9	30.5	22.5	19.2	15.7	14.3	11.7	9.7
19	56.5	40.7	31.1	23.0	19.6	16.0	14.6	12.0	10.0
20	57.7	41.5	31.8	23.5	20.0	16.4	14.9	12.3	10.2
21	59.0	42.3	32.4	24.0	20.4	16.7	15.2	12.6	10.4
22	60.2	43.2	33.0	24.5	20.8	17.1	15.5	12.8	10.7
23	61.5	44.0	33.7	25.0	21.2	17.4	15.9	13.1	10.9
24	62.7	44.9	34.3	25.5	21.7	17.8	16.2	13.4	11.2
25	64.0	45.7	34.9	26.0	22.1	18.2	16.5	13.7	11.4
26	65.2	46.6	35.6	26.5	22.5	18.5	16.8	13.9	11.7
27	66.5	47.4	36.2	27.0	22.9	18.9	17.1	14.2	11.9
28	67.8	48.3	36.9	27.5	23.4	19.2	17.4	14.5	12.2
29	69.0	49.1	37.5	28.0	23.8	19.6	17.8	14.8	12.4
30	70.3	50.0	38.1	28.5	24.2	20.0	18.1	15.1	12.7