Acoustical Measurements with Smartphones: Possibilities and Limitations

Benjamin M. Faber

Postal:
277 South 2035 West
Lehi, Utah 84043
USA

Email:
ben@faberacoustical.com

A smartphone-based sound level meter or analyzer may or may not replace your expensive, precision instruments.

Introduction

With an estimated 1.4 billion units sold globally in 2016 (GfK, 2016), smartphones constitute a ubiquitous mobile computing device, capable of performance comparable to that of high-end desktop computers of just a few years ago. Beyond their undeniably widespread adoption, smartphones are mediacentric devices, complete with microphones, cameras, wireless communications, and large touch screens. For those with a smartphone in their pocket, and particularly those interested in acoustics, this raises several questions such as, "Now that I have a microphone connected to a computer in my pocket, what can I measure with it?" and, "How good could the measurements be?"

The Signal Path

To answer such questions regarding the use of smartphones in acoustics, it becomes important to understand the path through which an acoustic signal must pass to be accounted for in any kind of measurement or analysis software. Although the signal path must obviously include some kind of transducer, such as a microphone or loudspeaker, there are other elements to consider, such as analog and digital electronics, device firmware, and operating system (OS) software. The focus of the smartphone on media creation and consumption leads to a relatively mature handling of audio signals. Existing smartphone-based solutions for acoustical measurement and analysis rely on this well-established audio signal path to provide convenience and low cost. **Figure 1** illustrates the most common audio connections for a smartphone.

Getting Signals Into the Device

The most obvious portion of the audio signal path may be the built-in microphone

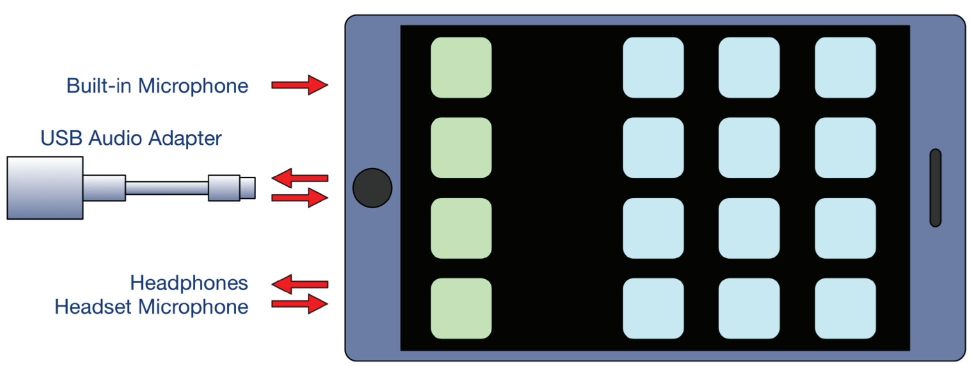

Figure 1. *Common audio input and output connections for smartphones and other mobile devices.*

of the smartphone. Although recent smartphone models often incorporate two or more microphones for noise reduction and/or beamforming for the purpose of enhancing speech signals, it is common to find a primary, omnidirectional microphone that may be most useful for typical acoustical measurements, such as the overall sound level.

The directionality of the microphone is an important parameter to consider when assessing the suitability of a particular smartphone as a measurement device. Dedicated sound level meters (SLMs) employ measurement microphones that are designed to exhibit a directional sensitivity that is as omnidirectional as possible. A microphone that exhibits a cardioid, supercardioid, or some other nonuniform directional pattern will be of limited value for overall sound level measurements because of its decreased sensitivity to sounds coming from certain directions. It is important to note that the shape of the smartphone body will itself have some impact on the directional behavior of its embedded omnidirectional microphone(s), especially at higher frequencies.

Beyond the built-in microphone, there are several other mechanisms available for getting signals into a typical smartphone. These include headset microphone input, Bluetooth and Wi-Fi wireless communications protocols, and electrical ports that can support either standardized (e.g., USB Audio Class driver) or proprietary protocols for data transmission. The audio signal path is currently best supported by standard protocols for Bluetooth and USB, but this does not preclude the existence of, or potential for, other proprietary solutions for acquiring acoustic signals with a smartphone.

The simplest mechanism for connecting an external measurement microphone to a smartphone is via the common headset jack. Most smartphones include a headset jack, which, in addition to serving as a headphone jack for audio output, supports a single microphone input. A typical headset microphone may have similar characteristics to the built-in microphone of the smartphone, but the headset jack makes it possible to connect a higher quality measurement microphone without the need for additional adapters or power sources. This means that using a microphone connected to the headset jack represents the most affordable and portable means for replacing the built-in microphone as the primary input source for higher quality measurements.

Getting Signals Out of the Device

For certain kinds of measurements, such as measuring the frequency response of a sound reinforcement system or the impulse response of a listening room, getting signals out of the smartphone can be just as important as the inputs. Smartphones typically have very small built-in loudspeakers with a limited frequency range or limited power output, but they also have a headphone jack through which signals can be transmitted to a power amplification system or directly to a device under test (DUT). In addition to built-in analog outputs, smartphones offer the same alternative signal paths for output as for input. That is, signals can potentially be transmitted over Bluetooth, Wi-Fi, USB, or some other proprietary interface.

Hardware Considerations

In addition to the directional behavior of the microphone, as mentioned previously, the frequency response, dynamic range, sensitivity, and other characteristics of the various hardware components within the signal path can significantly impact the accuracy and/or precision of a measurement. The presence of automatic gain control (AGC), for example, which is commonly used to optimize the acquisition of speech signals for telephony, may significantly diminish the accuracy of an overall sound level measurement, even though it may not adversely affect a measurement designed solely to identify specific frequency components of an acoustic signal.

Operating System Considerations

Once a signal of interest passes through the relevant hardware components into the digital domain, the OS of the smartphone takes ownership. Again, this new step in the signal path can potentially affect the viability of a measurement. One way for OS software to directly affect the potential for quality measurements is to offer mechanisms for controlling certain behaviors of the hardware components within the signal path. For example, if a hardware component, such as the analog-to-digital converter (ADC), employs its own form of AGC, then it may be possible for the OS to provide an application programming interface (API) to third-party apps to allow them to disable it for the sake of measurement accuracy. As another example, the OS may provide an API for adjusting the analog gain of the microphone input signal prior to digitization.

OS-level signal processing may also affect signal integrity. When third-party application software (an app) requests an input signal at a sample rate that is different from the hardware sample rate, the OS may resort to sample rate conversion, which requires some form of filtering that may have an impact on the frequency content of the signal. OS software may also include its own algorithms for manipulating the input audio signal to optimize it for telephony or automatic speech recognition. If an app developer has no way to circumvent OS-level signal-processing schemes or ensure the desired behavior of the various hardware components in the signal path, then it may be impossible to provide a reliably accurate or precise measurement solution by relying on the existing audio signal path. Fortunately, some OS-level APIs include options to bypass any extra signal processing that would significantly corrupt or distort the incoming audio signal (whether from the built-in microphone or some other audio input source). Of course, a solution that bypasses the well-established audio signal path in favor of a proprietary one could be developed. This kind of proprietary solution would require additional external hardware and would necessarily come at a higher cost.

A real-world example of the impact an OS can have on the signal path is shown in **Figures 2** and **3**. In some iPhone OS (iOS) versions before iOS 6, a high-pass filter was applied to both the built-in microphone signal and the headset microphone signal. The low-frequency effects of this filter can be seen in **Figure 2**. For measurement purposes, the microphone inputs of the iPhone were of limited value for frequencies below about 200 Hz. When iOS 6 was introduced in 2012, an API was added that allowed app developers to enable a so-called "measurement mode." The effect of enabling measurement mode, which also disabled AGC for the same input signals, is shown in **Figure 3**.

Calibration

An accurate sound level measurement requires that the smartphone solution be calibrated. Calibration refers to the comparison of a sound level measured by the smartphone-based meter and a properly qualified SLM with a known degree of accuracy. Once such a comparison is made, input sensitivity values with a smartphone app can be adjusted to produce results that match those of the reference SLM.

A digitized signal is represented by a series of numerical values that are less than or equal to some full-scale value (the maximum numerical value that can be represented by the ADC or the computing platform in which the digital values exist; FS). When calibrating the built-in microphone of a smartphone, the sensitivity of the microphone can be determined in pascals relative to the FS or Pa/FS. Once that sensitivity is known, it should be simple for a smartphone

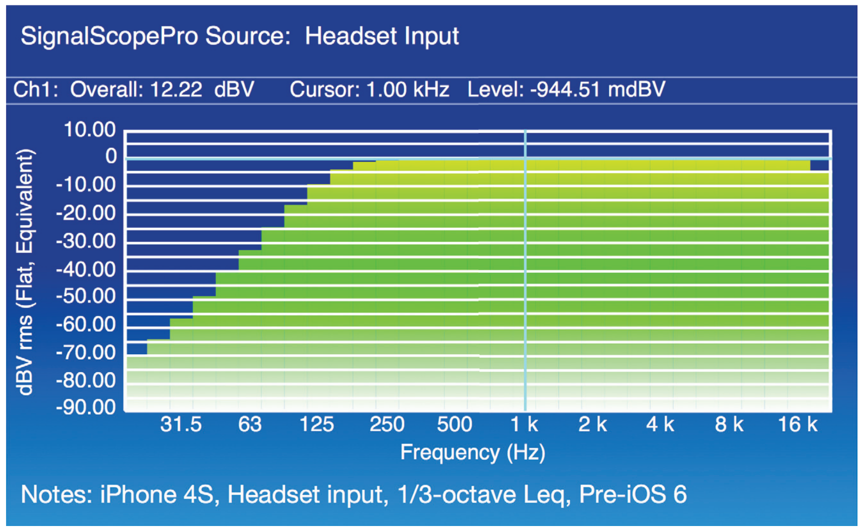

Figure 2. *One-third octave frequency response of the iPhone 4S headset microphone input, with measurement mode disabled (as it was in earlier versions of iOS). This measurement was made with SignalScope Pro.[1] Leq, equivalent (nonexponential) time weighting used to calculate the root-mean-square (rms) level of the signal in each one-third octave frequency band. Republished from Faber Acoustical (2012), with permission.*

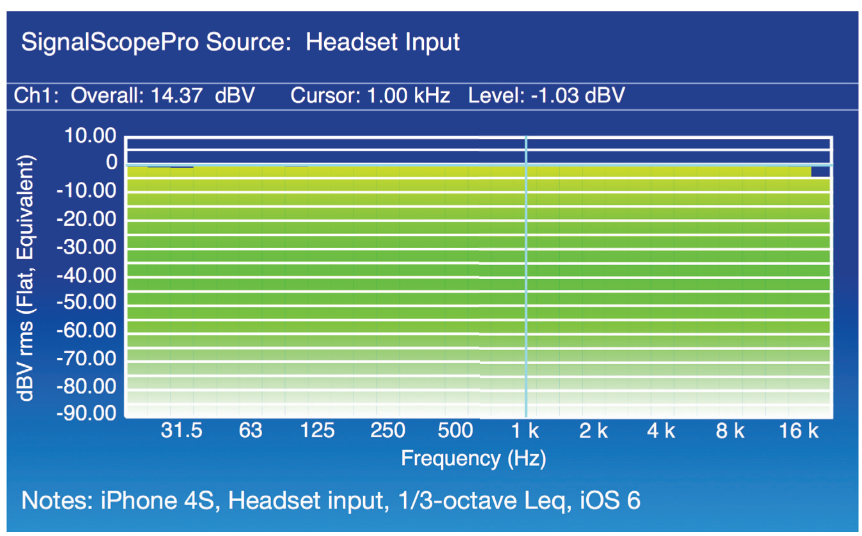

Figure 3. *One-third octave frequency response of the iPhone 4S headset microphone input, with measurement mode enabled. This measurement was made with SignalScope Pro. Republished from Faber Acoustical (2012), with permission.*

[1] SignalScope Pro is a product of Faber Acoustical, LLC, which is owned by the author.

app to use when calculating signal levels to determine an accurate sound level. Unfortunately, it can be difficult for many users to accurately measure the built-in microphone sensitivity, often because the user lacks a properly calibrated SLM to use as a reference and/or sufficient know-how to avoid significant measurement errors. Some smartphone apps include nominal sensitivities for select smartphone models that allow the user to make sound level measurements with ballpark accuracy without any additional equipment or effort.

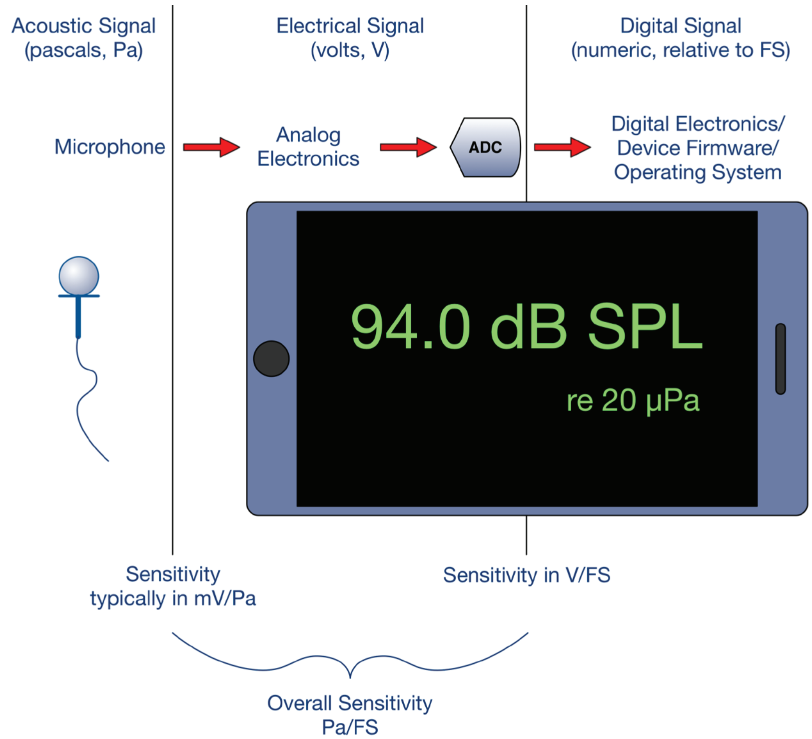

Figure 4. *The stages through which the original acoustic signal must pass in order to be used for measurement within a smartphone app. Properly calibrated transducer and electronics sensitivities allow the smartphone app to perform accurate acoustical measurements. SPL, sound pressure level; FS, full-scale value.*

When working with external measurement microphones, calibration can potentially be simplified or even obviated, depending on the required level of measurement accuracy. Often, a calibrated measurement microphone includes a certificate indicating the sensitivity of the microphone at a frequency of 1 kHz in units of millivolts per pascal (mV/Pa). If, as in a case such as this, the microphone sensitivity is known and it is connected to an analog audio input, then the input sensitivity must be determined in units of volts relative to the full-scale digital value of the ADC or V/FS. Once this is done, then the sensitivity of the microphone may be combined with the sensitivity of the input device to arrive at an overall sensitivity in Pa/FS, which can then yield an accurate overall sound level. The relationships between these different sensitivities are shown in **Figure 4**, which also illustrates the path through which the signal must pass for basic sound level measurements.

As before, if better than ballpark accuracy is critical, then a direct calibration of the microphone sensitivity, as part of the complete measurement system, is recommended. This becomes a simpler task when working with a measurement microphone that is designed to fit an acoustic calibrator with a standard (nominal) 0.25-, 0.50-, or 1-inch-diameter opening. With smartphone apps that support it, this approach makes the calibration procedure much easier for the user. The user simply needs to follow a process such as the following:

1. Connect the microphone to the smartphone.
2. Insert the microphone into the calibrator.
3. Tell the app the reference level of the calibrator.
4. Start the calibrator.
5. Press a "Calibrate" button in the app to go ahead and calibrate the sensitivity based on the actual acoustic pressure being applied to the microphone.

Suitability for Calibrated Measurements

Perhaps the most obvious answer to the first question, "What can I measure with it?" is that of overall sound levels. If sound levels can be determined easily enough with sufficient accuracy, the widespread use of smartphones presents the potential for unprecedented access to sound levels (and other acoustic parameters) in various environments across the globe. Researchers at the National Institute for Occupational Safety and Health (NIOSH) saw this potential and took action to begin to answer the second question, "How good could the measurements be?" and to determine the feasibility of acquiring widespread samples of occupational noise exposure. They have published their initial findings in two separate articles in *The Journal of the Acoustical Society of America Express Letters* (*JASA-EL*). The first publication presented research aimed at identifying specific smartphone apps that met certain requirements and then testing the performance of those apps with the smartphones' built-in microphones to determine their reliability for occupational noise measurements (Kardous and Shaw, 2014). Their second body of research focused on assessing a handful of inexpensive external microphones that could be connected to a standard 3.5-mm headset jack on a typical smartphone (Kardous and Shaw, 2016).

It is important to note that no smartphone-based sound level measurement solution has been shown to meet all the electrical and acoustical requirements for professional SLMs, as specified in the American National Standards Institute (ANSI; 1983) and International Electrotechnical Commission (IEC; 2013) standards, although some individual components of such a system, such as apps or microphones, may have been designed to meet those specifications. This is an important consideration because the entire system would need to be properly qualified by passing numerous tests as required by the standards. If a smartphone-based app were to be upgraded or a microphone replaced, the measurement system would potentially need to be requalified (not just recalibrated) for standards compliance. In light of the previous consideration of the acoustic signal path through a smartphone, even a routine update to the OS of the device could necessitate a requalification of the measurement system according to the standards.

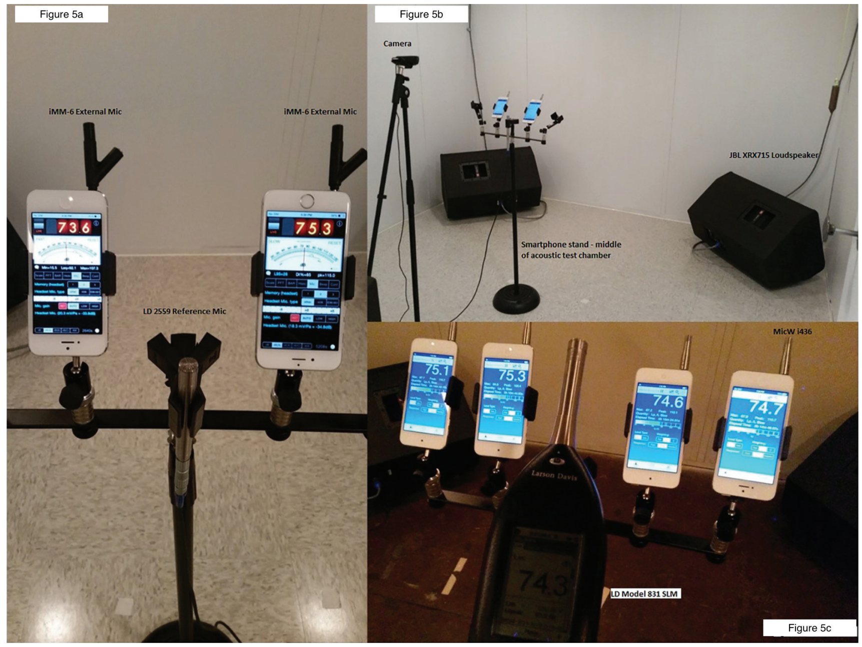

Figure 5. *Images of different test configurations within the National Institute for Occupational Safety and Health (NIOSH) acoustic test chamber. The chamber is designed to establish a diffuse sound field to minimize the effects of microphone size, orientation, and location on the results of the study.* ***a****: SPLnFFT app running on two iPhones with iMM-6 microphones set up for comparison to a Larson Davis 2559 (type 1) reference microphone.* ***b****: An expanded look at the reverberant test chamber.* ***c****: SoundMeter and i436 microphones connected to 4 different iPhones, with a Larson Davis 831 type 1 SLM for comparison. Image labels have been edited from the original. Republished from Kardous and Shaw (2016), with permission.*

Built-In Microphones

Smartphones typically employ MicroElectroMechanical Systems (MEMS) microphones. Although MEMS microphones exhibit a flat frequency response comparable to what can be expected of microphones used in type 2 instruments and can capture signals between approximately 30- and 130-dB sound pressure level (SPL), their signal-to-noise ratio (SNR) is currently limited to about 60 dB, which can have implications on the quality of acoustical measurements. The specification for sound level meters, published by ANSI, designates various types of sound level meters according to their level of accuracy. In the S1.4-1983 standard, a type 1 meter is designated a "Precision" instrument and a type 2 meter is designated a "General Purpose" instrument (ANSI, 1983).

In light of the aforementioned limitations, NIOSH researchers chose to investigate sound level measurement smartphone apps in terms of their ability to measure sound levels with an overall allowable error of ±2 dB(A) (Kardous and Shaw, 2014). After several criteria were established for the selection of smartphone apps, based on the interest of NIOSH in occupational noise exposure, over 130 sound level apps for iOS and 62 apps for Android were identified, from which 10 iOS apps and 4 Android apps were selected for closer evaluation. There were no Windows-based apps that met the selection criteria. Tests were conducted on a representative selection of popular smartphone devices.

From a host of measurements with different apps and devices, over a test range of 65- to 95-dB SPL, three iOS apps were found to have unweighted mean differences within ±2 dB of a type 1 reference SLM: NoiSee, SoundMeter[2], and SPLnFFT. There were also three apps found to exhibit A-weighted mean differences within ±2 dB(A) of the reference: Noise Hunter, NoiSee, and SoundMeter. Similar comparisons were not made with the four selected Android apps, in part because they only partially met the desired criteria. The testing performed with the Android apps also showed high variability in measurements across different devices. Even on iOS, with a much larger assortment of sound meter apps, an app may indicate a sound level, but it may not be measuring or calculating that sound level with any reasonable degree of accuracy.

It is important to note that this work used nominal microphone sensitivities provided by app developers; no calibrations were made. This allows for potentially more accurate

[2] SoundMeter is a product of Faber Acoustical, LLC, which is owned by the author.

measurements to be made with the built-in microphone after the user has performed his/her own calibration relative to a more accurate sound level meter. It also highlights one of the challenges faced by app developers, which is the need to determine reasonably accurate nominal sensitivities for any smartphone device to be supported by a sound measurement app. This presents a more daunting challenge for developers of Android apps because so many smartphone manufacturers offer so many different devices with potentially modified versions of the Android operating system.

External Microphones

Although the previous work clearly demonstrated the potential for reasonably accurate sound level measurements with smartphone apps (Kardous and Shaw, 2014), at least in a well-behaved environment, NIOSH researchers were interested to see what could be accomplished with relatively inexpensive, highly portable, external measurement microphones. In their follow-up study, Kardous and Shaw (2016) used similar tests to examine two different external microphones that may be connected to the analog headset jack of a smartphone. The study examined the Dayton Audio iMM-6 and the MicW i436. The i436, although more expensive, is claimed by the manufacturer to comply with the IEC 61672-1 Class 2 specification. It should be noted, however, that the IEC standard applies to the SLM as a complete measurement system, not to the microphone, alone (IEC, 2013). To investigate the relative performance of these microphones, the four iOS apps that were found to be most accurate in the previous study were used once again to measure sound levels ranging from 65- to 95-dB SPL in 5-dB increments. **Figure 5** offers a look at the test configurations used to compare the performance of various external microphones and apps.

The mean sound level differences for the external microphones, relative to a type 1 SLM, were much better than those previously obtained with the built-in microphones of the smartphones. The mean and standard deviation for external microphones were −0.023 and 0.530 dB, respectively, in contrast to 1.646 and 3.795 dB, respectively, for internal microphones. Both external microphones performed well in these tests, which suggests that even a very inexpensive microphone, such as the iMM-6, can be used for reasonably accurate measurements with a smartphone. The more robust construction of the i436 as well as its ability to fit a standard 0.25-inch adapter for an acoustic calibrator, may make the i436 more reliable in changing environmental conditions and easier to calibrate, but its higher cost will be justified according to the user's needs. A visual comparison of the relative performance of the internal and external microphones as well as of the four selected smartphone apps is shown in **Figure 6**.

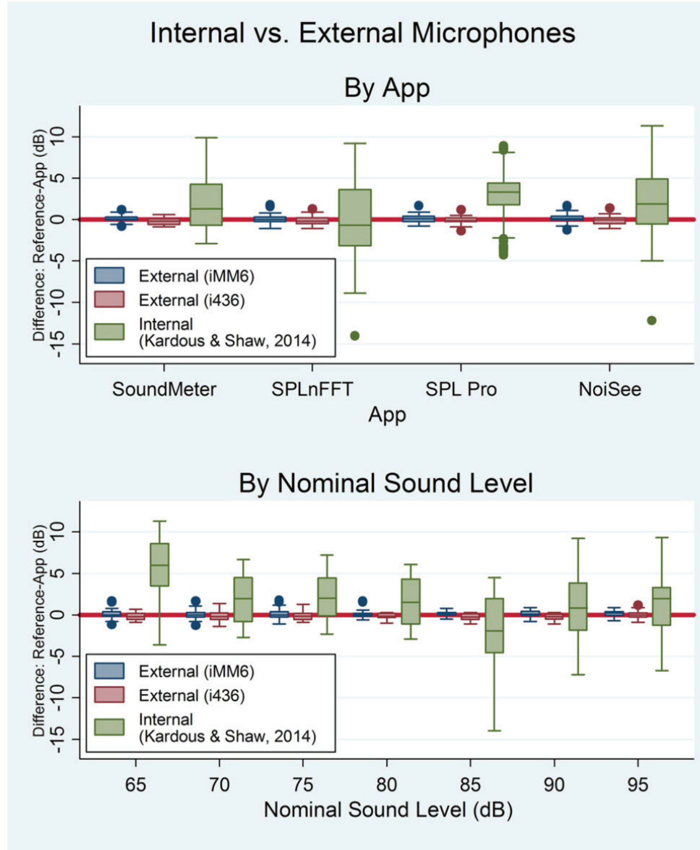

Figure 6. *Statistical distributions of differences between reference sound level meter (SLM) levels and app measurements with external and internal microphones are represented with box plots. The horizontal line inside the box represents the median value. The horizontal lines above and below the box represent maximum and minimum values, respectively. Extremely high or low values may be considered outliers and are represented as dots above or below the box plot. Results are shown by app (**top**) and by nominal sound level (**bottom**). Republished from Kardous and Shaw (2016), with permission.*

In another study, Roberts et al. (2016) also concluded that it may be possible to measure valid occupational noise exposure levels with smartphones and other "smart" mobile devices, with suitable apps and external measurement microphones. (See article by Enda Murphy in this issue of *Acoustics Today*.) The need remains to conduct additional research to better understand the suitability of smartphone SLMs for calibrated measurements in real-world conditions outside the laboratory. Even within the laboratory, there are other issues to investigate, such as frequency dependence, directional response, signal path linearity and distortion, and even user behavior. An investigation by Robinson and Tingay (2014) found that with carefully selected components, a smartphone-based system could be genuinely useful to a qualified professional but that there are enough potential pitfalls to make it difficult to generically recommend smartphone SLM apps to the general public.

Current Use of Smartphones in Acoustics

Publications continue to surface highlighting acoustics-related studies being performed with or for smartphones. A recent study took a look at the use of smartphones to introduce sound level measurement and the creation of sound maps to architectural acoustics students in Japan (Satoh et al., 2016). It was found that iOS devices and some Android devices offered sufficient accuracy for their needs and that the use of smartphones can help engage the students more deeply in their study. The Doppler effect was studied using smartphones in an educational setting at universities in Germany and Switzerland (Klein et al., 2014). Another study presented results from the measurement of room acoustics parameters using two iPhone models (Rizzi et al., 2015).

At the Salt Lake City meeting of the Acoustical Society of America in May 2016, a special session was held that was dedicated to the topic of noise measurements with mobile apps. Topics presented in that session included the use of smartphones for assessing noise exposure for preterm infants while being transported by helicopter to neonatal intensive care units (http://doi.org/10.1121/1.4950019); remote monitoring of noise levels in hospitals and industrial plants (http://doi.org/10.1121/1.4950018); and measuring noise exposure levels in exercise (indoor cycling) classes (http://doi.org/10.1121/1.4950021).

Although published research featuring smartphones for acoustical measurements seems to just be getting started, hundreds, perhaps thousands, of apps are already available from numerous developers for accomplishing a broad array of acoustics-related measurement and analysis tasks. The traditional functions of a benchtop dynamic signal analyzer, including time waveform monitoring, single or multichannel spectrum analysis, transfer function and impulse response measurements, and coherence and cross-correlation measurements, can be made with a smartphone, a suitable app, and, if necessary, external adapters or accessories. Apps related to music (tuners and recorders), speech (pitch and formant analysis), and audio (electroacoustic system tuning and equalization) have been available in smartphone app stores almost since the very beginning of the modern, touch-enabled smartphone era.

Present and Future Outlook

Although the notion of making acoustical measurements with smartphones is sometimes met with reasonable skepticism, evidence is growing to show that, by carefully selecting a device, an app, and a measurement microphone, even very accurate measurements can be made with a fairly high level of precision. The various components in the signal path and the potential for those components to change from day to day (particularly with software) require careful attention not only to see that accuracy is obtained initially but that it is maintained over time.

Regardless of the present inability of the smartphone to replace a type 1 SLM, there are other practical benefits to the use of sound measurement or analysis apps. These include promoting public awareness about the potential dangers of high noise exposure; making ballpark measurements to establish a need for more sophisticated measurements; identifying frequency components of desirable sounds or undesirable noises; educating students or the general public regarding basic sound measurement and analysis principles; and other personally or professionally beneficial activities.

The availability and capability of acoustics-related smartphone devices, accessories, and apps continue to expand, which suggests that exciting and accessible new tools will continue to emerge in the years ahead. The possibility of carrying an acoustical measurement suite in your pocket, with minimal added cost relative to that of the smartphone already there, is compelling for many.

Biosketch

Benjamin Faber studied acoustics at Brigham Young University (BYU), receiving a BS degree in electrical engineering and a MS degree in physics. Ben worked on energy-based active noise control both as a student and as a faculty research associate in BYU's Department of Physics and Astronomy until November 2006 and is coinventor on five awarded patents stemming from his work there. Since then, Ben has been fully engaged as owner of Faber Acoustical, LLC, which specializes in developing intuitive software applications (apps) for performing real-time signal analysis, measurement, and data acquisition, particularly for Apple's macOS and iOS.

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