A model of the VU (volume-unit) meter, with speech applications

Bryce E. Lobdell and Jont B. Allen
Beckman Institute, University of Illinois, Urbana, Illinois 61801

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The *Volume-Unit* (VU) meter, used in speech research prior to the advent of computers and modern signal processing methods, is described in signal processing terms. There are no known software implementations of this meter, which meet the 1954 ASA standard and provide the instantaneous needle level. Important speech applications will be explored, such as making comparisons of speech levels to earlier classic works, and measuring speech levels using traditional methods on modern computers. It is our intention to make this venerable method of measuring speech levels available once again. The VU meter is simulated and its properties are studied. A 1950s vintage and a recent vintage VU meter are studied by comparing the transient responses to tones and measurement of speech levels. Based on these measurements, a software VU meter (henceforth referred to as *VUSOFT*) is simulated, and verified. The method for reading the meter is explained, and simulated in software. The VU level for speech is shown to depend on the reading duration. The relationship between the root-mean-squared (rms) level of a signal and the VU level of a signal is determined, as a function of the meter-reading time. © *2007 Acoustical Society of America.*
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I. INTRODUCTION AND MOTIVATION

It is important to know how to make speech level measurements. Traditionally this was the job of the *VU meter*, an instrument which was used by radio engineers, audiologists, and speech perception scientists, to measure the level of speech sounds. Not every "sound level meter" having a microphone and needle is a VU meter. The VU meter is an industry standard device. Knowledge of speech VU levels are required for the proper interpretation of many speech perception experiments, since most of the early experiments depended on the VU speech levels (Castner and Carter, 1933).

Following the work of Fletcher and Steinberg (1930), the classic speech loudness measurements of Fletcher and Munson (1933) helped establish the importance of speech level measurements. French and Steinberg (1947) relied extensively on data from papers by Dunn and White (1940) and Sivian (1929). In particular, they used the average spectrum of speech and the cumulative level distribution versus long average intensity, in 1/8 s intervals. We shall show that the effect of a 1/8 s root-mean-square (rms) average is similar to that performed by a VU meter. During World War II, Harvard university adopted the methods developed at Bell Labs. For example, Miller and Nicely (1955) used a VU meter to control the signal-to-noise ratio (SNR) and speech level. When repeating such experiments, it is helpful (and arguably necessary) to have the VU meter measurement method available. As a result, a VU meter was obtained and simulated, as reported here.

Some of the issues developed here were touched upon by previous studies, namely Ludvigsen (1992) and Sjogren (1973). Sjogren compared the consistency of eight different speech level measurements, including the VU meter, by measuring the level of consonant-vowel-consonant (CVC) sounds and monosyllabic words relative to the level of a carrier phrase. Ludvigsen went on to conclude that measurement methods that integrated in time, such as the VU meter, were preferable to "impulse" measurements. Thus, the need remains for a software simulation of the VU meter.

The VU meter standard is described in detail. A 1950s vintage VU meter and a recent vintage VU meter are measured and compared to the VU meter standard. A simulation of the VU meter, denoted *VUSOFT* is described and verified. Finally, the effect of the VU meter-reading method on the VU level is described, and comparisons between the root-mean-squared (rms) level and the VU level are presented.

II. SUMMARY OF THE VU METER STANDARD

In response to the need for a standard and effective way of measuring program levels (i.e., music and speech) for transmission purposes, Columbia Broadcasting Systems, the National Broadcasting Company, and the Bell Telephone Laboratories devised and published materials (Chinn *et al.*, 1940) describing the device that would later be called the VU meter.

As described in Bohn (2000), in 1942 the American Standards Association (ASA) published a standard for VU meters (ASA, 1942). This standard was followed by the IRE standard in 1953 (IRE, 1953) also known as IEEE Standard #152-1953, and another ASA standard in 1954 (ASA, 1954), upon which our investigations are based. The most recent standard IEC 60268-17 (IEC, 1990) is not relevant to work published prior to 1990.

According to the ASA standard (ASA, 1954), the VU meter is the output of a full wave rectifier followed by volt meter, comprised of a mass, spring constant, and damping of the meter movement, whose response to a sudden and steady input should reach 99% of its final value within 0.3 ± 0.03 s, and shall overshoot its final value by at least 1%, but not more than 1.5%. The response of the VU meter to steady sine

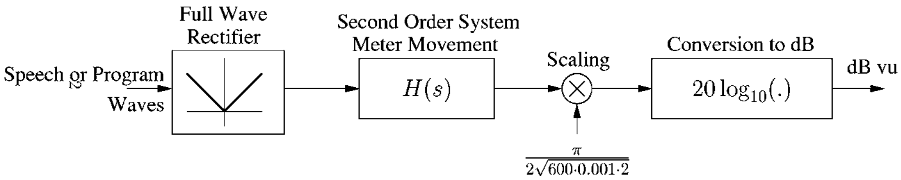

FIG. 1. Block diagram of the VU meter implied by the VU meter standard.

waves should not diminish more than 0.2 dB between 25 Hz and 10 kHz from the response to a 1 kHz sine wave. The VU meter output should be scaled to read in "dB vu" (while the standard says the unit is "VU," "dB vu" has become the accepted unit). Figure 1 shows the block diagram implied by the standard. The system described can be implemented on a computer by cascading the absolute value of the input voltage signal, with the proper second order system, and scaling and conversion to decibels. The second order system with the response described by the standard is a low-pass filter with a very low cutoff frequency (around 8 Hz). Conceptually, that means the VU level is a moving average of absolute value of the input signal. For periodic or steady signals such as a tone or noise, the VU level is the average absolute value of the signal. The parameters of the continuous and discrete time second order systems are derived in Appendix A. The MATLAB code that implements the VU meter standard is given in Appendix B, dubbed *VUSOFT*.

A VU meter reads in decibels, $20\log_{10}(V/V_{\text{ref}})$, where V is the meter voltage and V_{ref} is the level of a 1 kHz tone that will deliver 1 mW into a 600 Ω impedance. Thus $V_{\text{ref}} = (2/\pi)\sqrt{2\cdot 600\cdot 0.001}$ V, which is about −3 dBV.

A. Harmonic distortion

A full wave rectifier generates harmonics. In a discrete time simulation of a VU meter such harmonics alias, causing the simulated VU meter to breach the standard (i.e., no variations are allowed larger than 0.2 dB from the response to a steady tone at 1 kHz). This problem is solved by an upsample rate conversion of the discrete time input signal to at least eight times its original rate before the full wave rectifier (Oppenheim and Schafer, 1998).

B. Nonlinearity

The ASA standard refers to a nonlinearity in the rectifier used in VU meters "the exponent of whose characteristic is 1.2±0.2." A 1950s vintage VU meter was examined (further details in Sec. III and in Appendix C) to determine the effects of any such non-linearity on the ballistics of that VU meter. It was discovered that the VU meter faceplate is graduated in a way that removes the effect of the nonlinearity, and that has a negligible effect on the ballistics of the VU meter needle.

III. COMPARISON OF VU METERS TO THE STANDARD

VUSOFT was designed based on the specifications in Sec. II. The MATLAB code and derivation can be found Appendices B and A, respectively. To verify that *VUSOFT* implements the ASA VU meter standard correctly, it was compared with a 1950s vintage VU meter and a recent vintage VU meter. The 1950s vintage hardware VU meter was labeled "VOLUME INDICATOR, Type 911-B, Ser. No. D-8941, The Daven Co., Newark NJ." The recent vintage VU meter was manufactured by Simpson Electric Co. (520 Simpson Avenue, Lac du Flambeau, WI 54538). The transient responses of the three meters were compared, along with the peak VU level with short speech sounds.

A. Methods for transient response comparison

The response of a second order system can be described by any two of several parameters. The two easiest parameters to measure are the peak time t_p and the overshoot M_p. The peak time t_p is the amount of time it takes for the step response of a system to reach its highest level. The overshoot is the amount by which the step response of a system will exceed its final value. The overshoot is measured by applying a long-duration reference tone and then noting by how much the meter needle exceeds its final value. The peak time is measured by playing successively longer reference tones, until increasing the length of the reference tone no longer increases the maximum level the needle reaches. The length of the tone at which the maximum level reached no longer increases is taken as the peak time.

B. Results for transient response comparison

Figure 2 shows the step response of the three VU meters. Note that the 1950s vintage hardware VU meter used

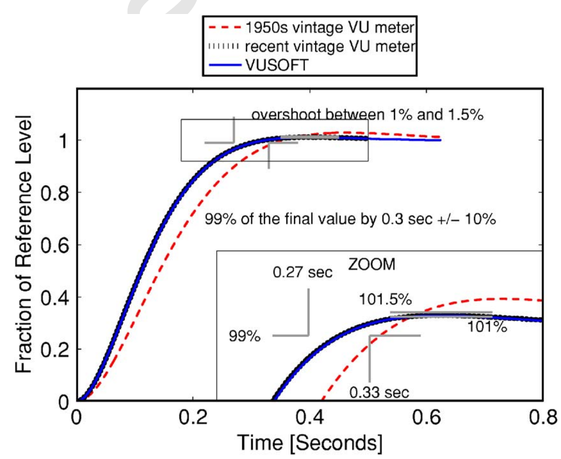

FIG. 2. (Color online) This figure shows the step response of *VUSOFT* and the two hardware VU meters. The stimulus is 1 kHz reference tone. This figure shows the instantaneous output of the second order system shown in Fig. 1 after scaling and before the conversion to decibels. The ordinate is scaled so that the reading is unity (0 dB vu) in response to the reference tone after the needle movement has had time to settle.

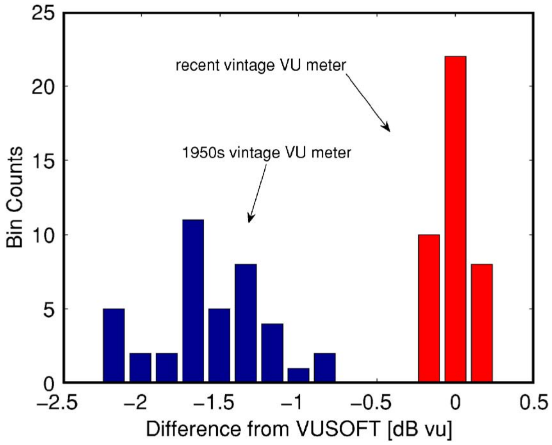

FIG. 3. (Color online) A histogram of the peak level recorded by the hardware VU meters in response to short speech recordings. The short speech recordings were scaled so that their peak level measured by *VUSOFT* was 0 dB vu.

in this study does not meet the ASA specification, since the overshoot is too large, and it has a slightly longer rise time. This difference in the transient response causes an average difference in the VU reading for short syllables of −1.6 dB, as shown in Fig. 3. The recent vintage VU meter meets the specified transient response, as does *VUSOFT*.

To understand the sensitivity of these differences with speech as the input, we measured peak VU meter levels of 40 speech recordings. We tested speech material consisting of isolated consonant-vowel pairs. A computer was used to store and play back the sounds into the two hardware VU meters, and the largest displacement of the VU meter needle was recorded. All speech sounds were normalized to read 0 dB vu using *VUSOFT*. A calibration tone, specified by the ASA standard (ASA, 1954), was used to assure that all three VU meters were identically calibrated.

C. Speech level results

Figure 3 shows a histogram of the peak VU levels of the hardware VU meters and *VUSOFT*. The mean difference between 1950s vintage VU meter and *VUSOFT* is −1.6 dB vu, with a standard deviation of 0.37 dB vu. The mean difference between the recent vintage VU meter and *VUSOFT* is 0.009 dB vu with a standard deviation of 0.09 dB vu. The recent vintage VU meter provides readings that are more consistent with *VUSOFT*, because they have more similar transient responses.

D. Radio Shack "sound level meters"

Two Radio Shack digital and analog meters (catalog numbers 33-2055 and 33-4050) were purchased and tested to determine if they would be a suitable substitute for a VU meter. The peak responses of these instruments are shown in Fig. 4, compared to *VUSOFT*. The digital sound level meter has a peak response that rises much faster than *VUSOFT* and thus also faster than the ASA standard), while the analog meter response is slower. It was also determined that the response of both of the Radio Shack sound level meters depends on the SPL range setting (i.e., the transient response is

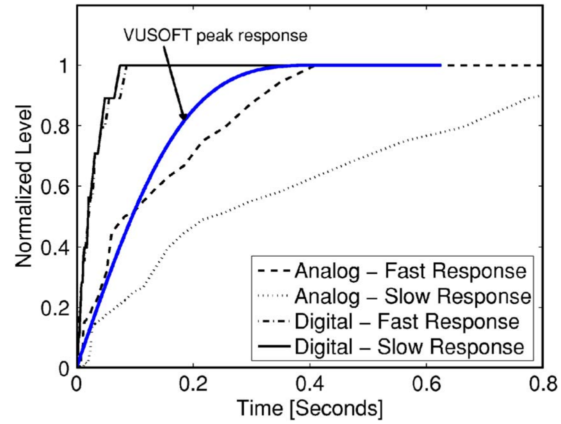

FIG. 4. (Color online) Peak response of Radio Shack sound level meters.

different depending on whether it is set to read 60–70 dB or 70–80 dB, etc.). Thus, as noted in Radio Shack's manual, neither of these meters conforms to any VU meter standard specification.

IV. READING THE VU METER

Reading a VU meter is more of an art than a science. The duration of the recording turns out to be a critical variable, as we shall show next. With regard to the reading method, the ASA standard for VU meters reads as follows (ASA, 1954):

> The reading is determined by the greatest deflections occurring in a period of about a minute for program waves, or a shorter period (e.g., 5 to 10 s) for message telephone speech waves, excluding not more than one or two deflections of unusual amplitude.

The authors asked several "experts" how they read VU meters. We were told by to pick the three highest levels for a segment of speech material and average them together. This method is claimed to be less subjective, and purported by the experts to be the true "standard method" for reading the VU level of speech material.

Figure 5 shows the waveform of a speech signal along with the *VUSOFT* output. High speech levels occur less frequently than low speech levels. Due to the small probability of the tails of the probability distribution, the longer the recording, the higher the peak level. In other words, "The longer you measure, the larger the VU level you will record." The goal in the following study is to quantify the relationship between the rms level, the time duration of the speech sample, and the peak VU level.

Our results are derived from a histogram of the *VUSOFT* output for 26 hours of speech as well as a count of the *VUSOFT* output peaks and the amplitude of those peaks. VU levels reported on in this section were generated exclusively by *VUSOFT*. All the speech material was normalized to the same rms level (computed over the whole speech file, typically several minutes). The speech material was from a corpus titled "ICSI Meeting Speech" produced by the Linguistic Data Consortium (http://www.ldc.upenn.edu), catalog number 2004S02. The speech involved approximately equal

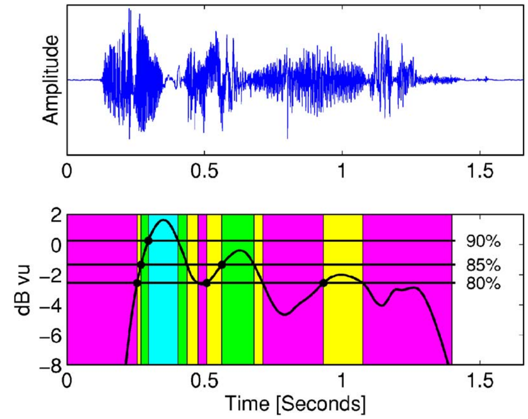

FIG. 5. (Color online) The top panel is the acoustic waveform for the phrase "No one pronounced zing seventh." The bottom panel is the *VUSOFT* output for that phrase time aligned with the acoustic waveform. The horizontal lines show the 80%, 85%, and 90% VU meter levels, denoted the *percentage of intervals*, as defined in the text.

numbers of male and female talkers conversing. This speech material was chosen because it was conversational in nature, involved a large number of speakers, and was never compressed or otherwise modified.

Figure 5 illustrates the peaks in the VU meter output for a particular speech phrase. The term *percentage of intervals* refers to the VU level compared to the distribution of VU levels (with VU levels sampled periodically). When we speak of a *percentage level of 90%*, the level is greater than 90% of other levels observed in speech for a fixed speech rms level. The horizontal lines in Fig. 5 show the 80%, 85%, and 90% levels for a particular speech recording.

A. VU meter and the level distribution of speech

The solid line in Fig. 6 shows the cumulative distribution of VU levels relative to the rms of speech. This figure was generated by computing levels for the speech material described above, and making a histogram of those levels. The histogram was converted to a cumulative level distribution where the levels are given relative to the rms level.

The dashed line in Fig. 6 is the result from Fig. 4 of French and Steinberg (1947), which was computed from the data of Dunn and White (1940) and Sivian (1929). It is not surprising that the relationship for the cumulative distribution of VU levels is similar to the result of Dunn and White (1940) because the meter has a similar frequency response to the 1/8 s window used by Dunn and White (1940), as illustrated in Fig. 7.

Figure 8 shows the relationship between the time duration that the VU meter level is monitored and the ratio of the VU peak level and the rms level, in dB. For each level the number of peaks of that level were counted. The average length of time between the peaks of each level was computed by dividing the length of the speech material by the number of peaks counted. This figure is particularly important because it allows one to compare the VU meter method described in the ASA standard to the rms level.

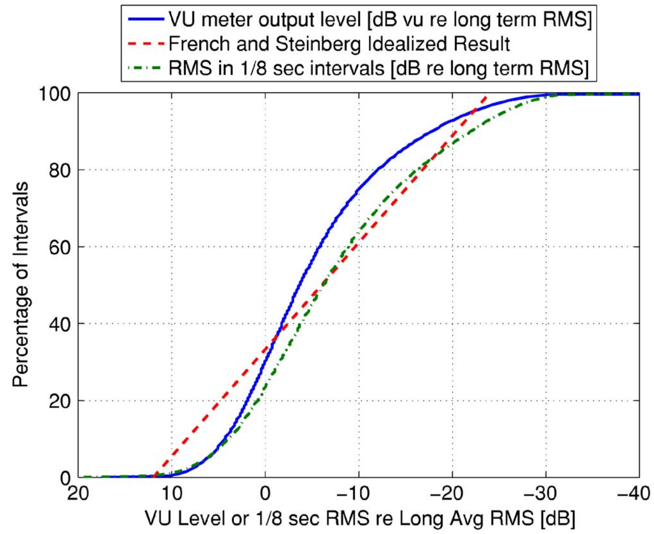

FIG. 6. (Color online) The solid line shows the cumulative distribution of VU levels (generated by *VUSOFT*) relative to the rms of speech, and compares it to the method of level measurement used by Dunn and White (1940). The dash-dotted line shows the cumulative distribution of rms levels in 1/8 s intervals, which is identical to the data shown in Fig. 4 of French and Steinberg (1947), taken from Dunn and White (1940). The idealized result of French and Steinberg is shown with the dashed line. For the solid line, the abscissa is the VU level (in dB vu) minus the long term rms level in decibels (computed over the whole speech recording, typically several minutes). For the dashed and dash-dotted lines, the abscissa is the ratio (in decibels) of the rms in 1/8 s intervals to the long term rms level. The ordinate is the percentage of 1/8 s intervals or VU levels (equally spaced in time) that are greater than the level shown on the abscissa.

V. RESULTS AND DISCUSSION

We are unaware of any ASA (1954) compliant software VU meter simulations that provide the instantaneous numerical needle position. Such a software simulation is necessary for comparison with other speech level measures (such as rms) and also automated level control using the VU meter in modern computer controlled speech experiments.

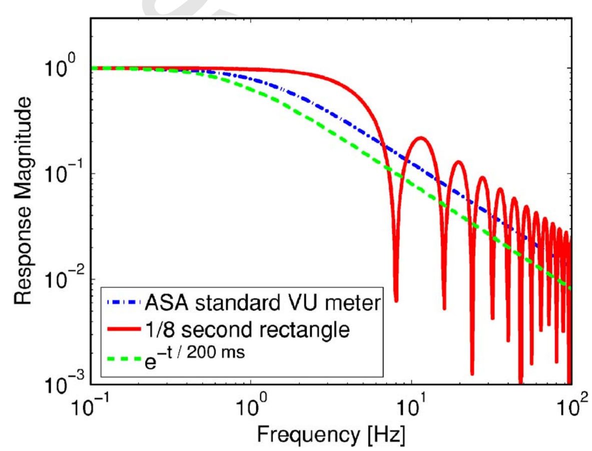

FIG. 7. (Color online) The dashed line shows the frequency response of the 200 ms integration related to the loudness of tones, described by Munson (1947). The solid line shows the frequency response of the 1/8 s window used by Dunn and White (1940) and Sivian (1929) to measure speech levels. The dash-dotted lines shows the frequency response of the second order system described by the ASA VU meter standard.

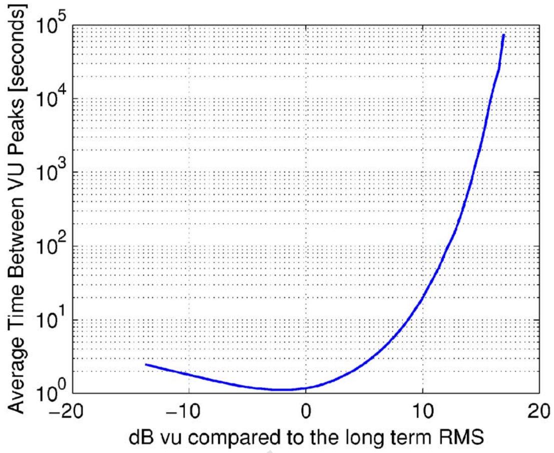

FIG. 8. (Color online) The duration between VU peaks (log s) as a function of the VU level peak level divided by the long terms rms (dB).

The ideal VU meter is a full wave rectifier followed by a second order low-pass system. The VU meter level is reported in dB vu referenced to a 1 kHz sin wave that will dissipate 1 mW into a 600 Ω resistor. A MATLAB© code (called *VUSOFT*) that implements the standard can be found in Appendix B.

Our VU meter reading method is to observe the highest peak. Figure 8 shows how the largest peak depends on observation duration. The ASA specified reading methods states that the VU level is the "greatest deflections occurring in a period of about a minute for program waves, or a shorter period (e.g., 5 to 10 s) for message telephone speech waves, excluding not more than one or two deflections of unusual amplitude." From Fig. 8 we conclude that the VU level observed over 5 to 10 s intervals will be 6–9 dB higher than the rms level, and that the VU level observed over a 1 min interval will be roughly 12 dB higher than the rms level.

The transient response of a 1950s vintage VU meter and a recent vintage VU meter were evaluated to confirm that we have accurately duplicated their behavior with *VUSOFT*. All three VU meters were very close to the standard specified response, leading us to conclude that we had properly interpreted the standard and duplicated it in *VUSOFT*. The 1950s vintage VU meter had an overshoot of which was 1.75% greater, and a peak time 0.06 s longer than that of the standard, while the recent vintage VU meter had a nearly identical transient response to the standard (Fig. 2). For short speech sounds, the peak level measured by the 1950s vintage VU meter was 1.6 dB vu lower on average than that measured by *VUSOFT*, while for the same set of speech sounds, the recent vintage VU meter differed from *VUSOFT* by 0.009 dB vu, on average.

The transient response of two Radio Shack "Sound Level Meters" were compared to the transient response of the VU meter to determine if they would make a suitable substitute for a VU meter. The sound level meters had a significantly different transient response and therefore would result in different observed levels.

The *sound level meter* standard published by the American National Standards Institute (ANSI) is different from the ASA VU meter standard, and will provide different level measurements for speech as a result of its different transient response. For example, the ANSI meter standard indicates that the needle level shall have an overshoot of 0 to 1.1 dB for the "fast response" setting and 0 to 1.6 dB for the "slow response" setting, which is significantly larger than the 0.09 to 0.13 dB overshoot specified for ASA standard VU meters. An ANSI sound level meter could potentially be used to measure speech levels, however, the specifications are less tight than the ASA VU meter standard and would therefore not be conducive to reproducibility between sound level meter instruments.

It is important when measuring speech levels to know that the transient response of the measurement device has a significant impact on the observed level, that the "VU meter" has tight specifications, and that not every level measurement device is a VU meter. Figure 2 and 3 illustrate how a small difference in transient response leads to an average difference of 1.6 dB vu for short speech sounds. The intensity just noticeable difference (JND) is less than this value.

The noise level and the signal-to-noise ratio (SNR) are critical components of many types of speech perception experiments; thus we would like to know how the rms measurement of noise compares to the VU-based measurement. For Gaussian noise the average absolute value is $\sigma\sqrt{2/\pi}$, where σ^2 is the variance of the noise (measured in volts squared). The VU level of the noise is then $20\log_{10}(\sigma/\sqrt{4\cdot 600\cdot 0.001/\pi})$ which is numerically equal to $20\log_{10}\sigma + 1.17$ dB vu, where σ has the unit of volts (rms).

In summary, users of VU meters should be aware that the VU level still has important applications, that a VU meter is a standardized device with tight specifications, and that it is possible to relate the VU level for different methods of reading the VU meter with the rms level.

ACKNOWLEDGMENTS

The authors would like to thank Mead Killion for his expert advice and assistance in obtaining VU meters.

APPENDIX A: DERIVATION OF THE VUSOFT DIFFERENCE EQUATION

The ASA standard says that the VU meter needle should have a response that overshoots by 1% but not more than 1.5% and that reaches 99% of its final value in 0.3 s. Results from linear systems analysis can be used to derive the parameters for a continuous-time system which has the required response. Details can be found in Ogata (1997).

A second order mass-stiffness system has a frequency response defined by the Laplace transform,

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad s = j2\pi f, \tag{A1}$$

where ω_n is the undamped natural frequency of the system, ζ is the damping ratio, s is the Laplace variable, and f is the frequency in Hz. The parameters ω_n and ζ conveniently specify the step response of a 2nd order system, which is

$$c(t) = 1 - e^{-\zeta\omega_n t}\left(\cos\omega_d t + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\omega_d t\right), \tag{A2}$$

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$$\omega_d = \omega_n \sqrt{1-\zeta^2}.$$

The parameters for the second order system can be computed by combining Eq. (A2) with

$$M_p = e^{-(\zeta/\sqrt{1-\zeta^2})\pi} \quad \text{and} \quad c(t_r) = 0.99, \tag{A3}$$

where M_p is the overshoot (i.e., M_p=0.0125) and t_r is the time the system takes to reach 99% of its final value (i.e., t_r=0.3 s). The equation $c(t_r)=0.99$ is the constraint that the step response $c(t)$ reaches 99% of its final value in t_r seconds. Combining these equations, we find that the second order system that describes the VU meter needle ballistics has parameters $\zeta=0.812\,72$ and $\omega_n=13.512$.

For our simulation we need a discrete time version of this system, which may be found using the bilinear transform having a z-transform (Oppenheim and Schafer, 1998), given by

$$H(z) = \frac{b_0 + 2b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2}}, \tag{A4}$$

where $z=e^{j\omega}$. The corresponding difference equation is

$$a_0 y[n] = a_1 y[n-1] + a_2 y[n-2] + b_0 x[n] + 2b_1 x[n-1] + b_2 x[n-2]. \tag{A5}$$

The following parameters are computed using the bilinear transform: $b_0=2b_1=b_2=T_d^2\omega_n^2$, $a_0=4+4\zeta\omega_n T_d+\omega_n^2 T_d^2$, $a_1=-8+2\omega_n^2 T_d$, and $a_2=4-4\zeta\omega_n T_d+\omega_n^2 T_d^2$, and T_d is the sampling period for the discrete time system. For example, at a sampling rate of 44.1 kHz, $b_0=b_2=9.3876\times10^{-8}$, $b_1=4.6938\times10^{-8}$, $a_0=4.0010$, $a_1=-8.0000$, and $a_2=3.9990$.

APPENDIX B: MATLAB CODE FOR VUSOFT

The ASA VU meter specifications relevant to a software VU meter simulation are met by the following lines of the MATLAB code (©Bryce Lobdell 2006) (http://www.auditorymodels.org/lobdell/vusoft/vusoft.m):

```
function y=vusoft (x, fs)
% Copyright 2006, Bryce Lobdell
% Parameters for the system:
% Td=1/fs/d⇒oversample by 8x to prevent aliasing.
wn=13.5119; eta=0.8127; D=8; Td=1/fs/D;
% Parameters for the filter:
B=Td^2*wn^2*[1 2 1];
A=[(4+4*eta*wn*Td+wn^2*Td^2)(−8
+2*wn^2*Td^2)...(4−4*eta*wn*Td+wn^2*Td^2)];
% Scale:
scaling=pi/2/sqrt(600*0.001*2);
% Upsample the input signal by 8x.
x_u=resample (x, D, 1, 50);
% Apply the absolute value, and the filter.
y1_u=scaling*filter(B,A,abs(x_u));
% Downsample back to the original rate.
y1=y1_u(1:D:end); y=20*log10(y1);
```

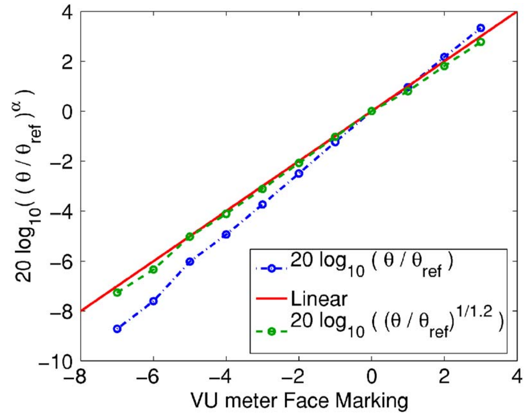

FIG. 9. (Color online) This figure shows the relationship between the needle angle and VU markings. If the dash-dotted line had a slope of one, the meter angle θ would be proportional to the voltage applied to the meter and rectifier package. The meter face is marked to compensate for the slope of 1.2, due to the meter's current I to voltage V relationship given by $I \propto V^{1.2}$.

APPENDIX C: NONLINEARITY OF THE RECTIFIER

The ASA standard ASA (1954) says that the VU meter shall be equivalent:

> "to the response with a direct current meter and a rectifier, the exponent of whose characteristic is 1.2±0.2"

We interpret this excerpt to mean that the current-voltage characteristic of the rectifier is θ (needle angle) $\propto I \propto V^{1.2}$. Several measurements were done to verify the exponent on the meter reading using a 1 kHz tone of varying level. Figure 9 shows the needle angle compared to the marked VU level. The dash-dotted line shows the needle angle θ measured with a protractor, compared to the marked VU level. The dashed line shows the relationship between $(\theta/\theta_{ref})^{1/1.2}$ and the VU level, which is linear. This implies that the meter current is proportional to $(V/V_{ref})^{1.2}$. It was verified that the VU meter face markings compensate for the non-linearity in the rectifier by comparing the VU level of tones of various levels.

The rectifiers used were most likely the copper-oxide type, as described in detail by Brattain (1951).

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