A Loudness-Level Monitor for Broadcasting

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Abstract—**A Loudness Monitor for broadcasting has been developed by CBS Laboratories under joint sponsorship with the CBS Broadcast Group and is currently undergoing field tests. The Monitor uses the CBS Laboratories equal-loudness contours, the Loudness Level Summation Method described previously by Bauer and Torick,[7] and a revised ear ballistics characteristic. The steady-state calibration of the Monitor is in decibels re 1 mW into 600 Ω at 1000 Hz. The indications of the loudness level of program are in loudness level units (LU).**

I. INTRODUCTION AND REVIEW

During the past several years, CBS Laboratories has been concerned with solving the problem of measuring and controlling the loudness of broadcast sounds with the objective of developing a meter for monitoring the program loudness, in much the same manner as vu meter monitors program "volume." Furthermore, it was anticipated that such a meter might lead to a future development of an automatic device for guarding against excessively loud program material. This effort has now reached the stage where a Loudness Monitor is available for field tests, and an automatic loudness controller is nearing the same milestone.

This paper is concerned with the Loudness Monitor. Before proceeding with its description, we would do well to review briefly the principles underlying the measurement of loudness and the studies that have led to the design of the Loudness Monitor.

II. VOLUME VERSUS LOUDNESS

To control the magnitude of the audio program, the broadcast engineer most frequently uses a volume indicator (VI).[1] In simplest terms, the VI is a rectifier-type, ac voltmeter with a movement fast enough to reach reference deflection in 0.3 s, and damped well enough to prevent more than 1-percent overshoot. The VI is calibrated in decibels. When measuring the volume of a program, the VI readings are called volume units (vu).

The VI has played a major role in improving the quality of broadcast sound because it offered a standardized and convenient means for monitoring the average program peaks in a manner approximately related to the modulation capability of a radio transmitter. Operating experience has confirmed, however, the known fact that the VI does not measure loudness. Programs exhibiting equal VI readings often differ greatly in loudness.

III. LOUDNESS DEFINED

"Loudness" is defined by the American Standards Institute[2] as "the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud." Since loudness is a sensation, it involves physiological and psychological processes of the listener which at present are not directly measurable. There is no direct and simple way to determine "how loud" a person has perceived a given sound.

However, we can get at a measure of loudness by indirect means. For this purpose, we must ascertain the manner in which typical listeners react to sounds of various types, and we must measure the physical attributes of those sounds. With this knowledge, we can hypothesize a model of a meter for combining these phenomena into a single reading in a manner corresponding to the sensation of loudness. It goes without saying that individuals will disagree to some extent with the readings of such a meter, but if the factors which influence the sensation of loudness have been correctly evaluated, the disagreement should be small. A point of caution is needed: a listener does not normally divorce his judgment of loudness from other influences such as annoyance or message content. For example, a newscast at a comfortably loud level for those who are interested in it may be "too loud" for those who are concentrating on a different endeavor such as, for example, trying to fall asleep. Thus we recognize two types of loudness:

1) Perceptual or Psychological Loudness, which includes the annoyance or emotional content of the message, and
2) Sensory or Physiological Loudness, which results from the action of the physical properties of sound upon the individual's mechanism of hearing.

It is quite evident that the measurement of the psychological factors in loudness presents much greater difficulties than the measurement of physical, or sensory, factors. Therefore, our efforts were directed only to this latter aspect of loudness.

IV. LOUDNESS LEVEL

To most people, the concept of "tagging" a sound with an absolute number corresponding to loudness is somewhat illusive (although, in some instances, acousticians have succeeded in doing this!). But, there is another concept in measuring loudness which is much easier to accept: most people listening alternatively to two dissimilar sounds find it quite easy to decide which

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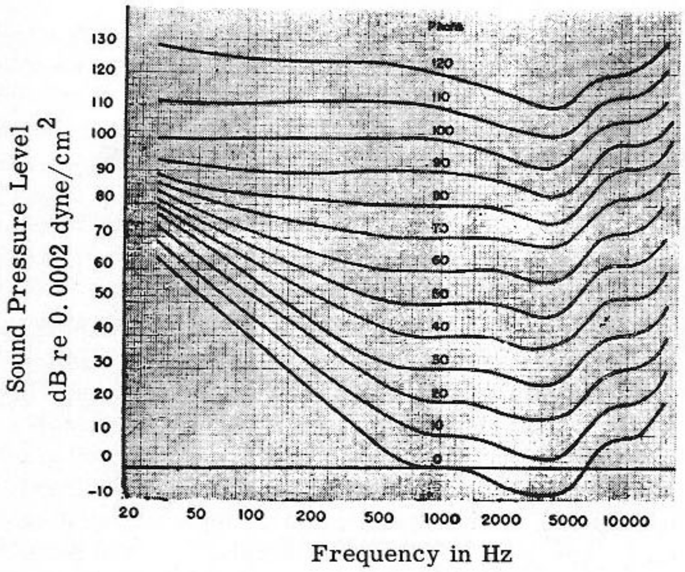


Fig. 1. Equal-loudness contours (Fletcher and Munson).

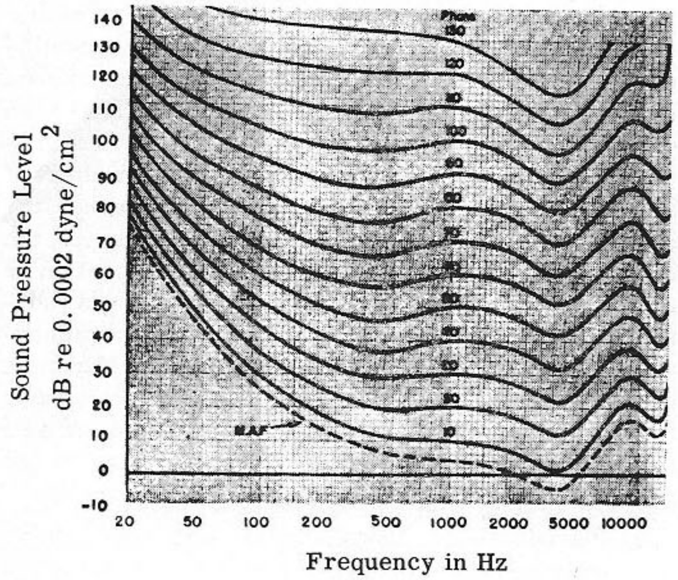


Fig. 2. Equal-loudness contours (Robinson and Dadson).

one is the louder and to adjust the volume of one of the sounds until the loudness of both is equal or "balanced." Now, when one of these sounds is a 1000-Hz tone of known sound pressure level, then by common agreement the unknown sound is said to have the same "loudness level" as the sound pressure level of the 1000-Hz tone.

It has been established experimentally that most listeners, after a bit of practice, will balance the loudness level of two sounds within an average variation of 1 dB. The well-known equal-loudness contours of Fletcher and Munson[3] were obtained by this loudness balance process. Initially, the observers, placed in an anechoic chamber facing the source of sound, were subjected to 1000-Hz sounds of known sound pressure level alternated with test sounds of varying frequencies. The listeners were asked to judge if the test sounds were louder or softer than the reference. Because of instrumentation difficulties, subsequent work was done with the aid of calibrated earphones. The procedure was repeated in 10-dB steps of the 1000-Hz tone, resulting in the set of curves shown in Fig. 1. While the researches of Fletcher and Munson are still highly regarded, more recent measurements by other investigators have resulted in revisions of the shape of these contours.

For example, in 1956 Robinson and Dadson[4] in England obtained the different set of contours shown in Fig. 2, which have gained acceptance in Europe but not in the United States. One important difference between the Fletcher–Munson and Robinson–Dadson contours is that while the former show considerable difference in shape between successive contours from 60 dB up, the latter are of relatively constant shape in this region. This behavior, also confirmed by ourselves and by others, suggests the possibility of devising a Loudness Level Meter with unvarying frequency response over at least a moderate range of levels.

V. Sound Level Meter

By combining microphone, amplifier, meter, and switchable weighting contour networks based on the work of Fletcher and Munson (called A, B, and C), devices known as sound level meters (SLM) have been produced and various models of such devices are at present manufactured to meet agreed-upon standards.[5] The reading of an SLM is called "sound level" or "noise level" and is given in decibels re 0.0002 dyn/cm^2 (microbars), together with the statement of the contour network used. The SLM is useful for comparative measurements of steady-state sounds, such as machinery noise, etc. The SLM, together with a band-frequency analyzer, is also useful for determining the band-pressure levels of steady-state noises which can be entered into a graph for the calculation of loudness.[6] However, the SLM does not measure correctly the loudness level of broadcast programs for three reasons.

1) There is an uncertainty as to which weighting contour to use for specific impulsive sounds.

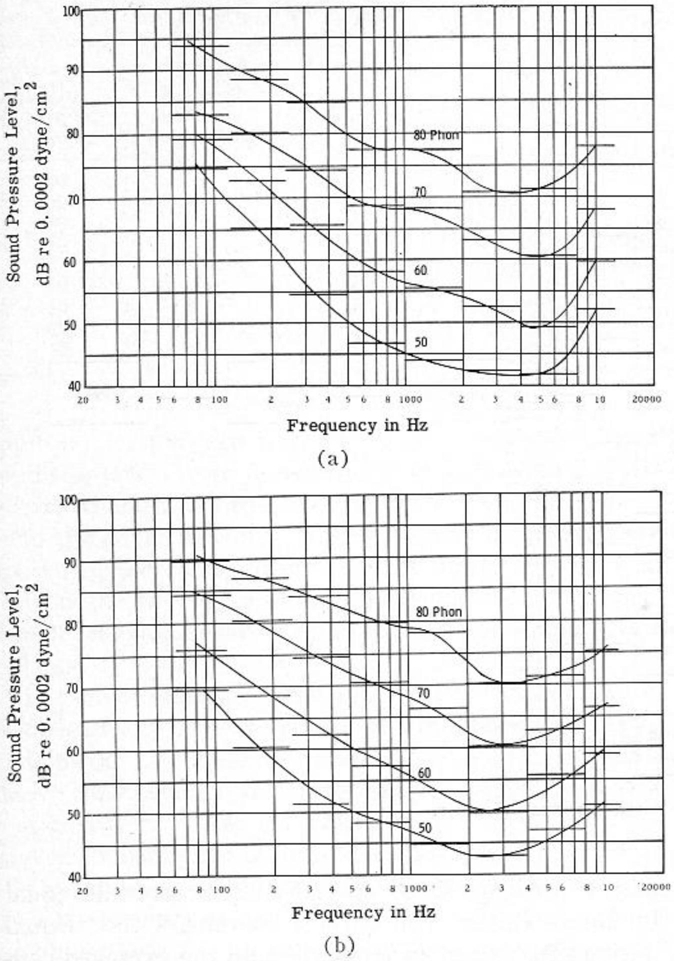
2) When a composite sound is measured with the SLM, the voltage contributions of the individual compounds add up as the root-mean-square. It has been shown by ourselves and others that this does not lead to correct overall loudness level indications.

3) The ballistic characteristics of the indicating instrument for impulsive sounds do not match those of the human ear.

VI. Projecting a Loudness Level Monitor

During the initial research phase described by Bauer and Torick,[7] the following essential facts were developed.

1) A new set of equal-loudness contours was obtained under simulated living room environment, using a loudspeaker, not earphones. In order to break up standing



(a)

(b)

Fig. 3. (a) CBS Laboratories' equal-loudness contours (female observers), octave bands of pink noise. (b) CBS Laboratories' equal-loudness contours (male observers), octave bands of pink noise.

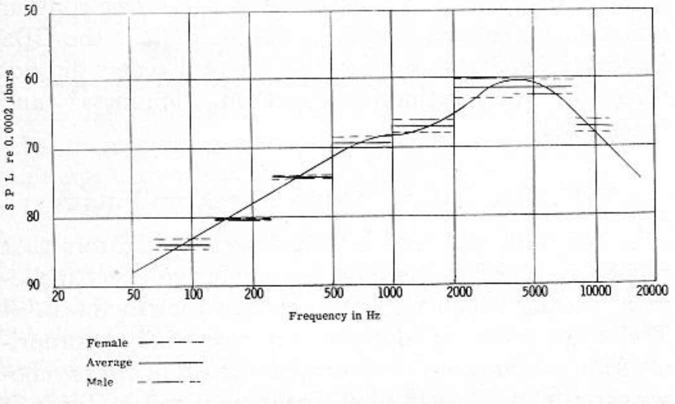


Fig. 4. Inverted average 70-Phon equal-loudness contour for pink noise octave bands (CBS Laboratories).

waves, octave bands of "pink noise"[1] were used instead of steady-state tones. These contours are shown in Fig. 3(a) for women and in Fig. 3(b) for men. The CBS Laboratories contours are less convergent at low frequency than

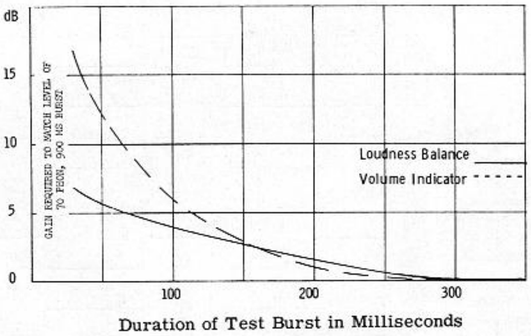


Fig. 5. Power level of 70-dB loudness level octave-band tone bursts.

the Fletcher–Munson contours, confirming the plausibility of using a constant frequency characteristic over a moderate range of levels. From these two basic contours a new average 70-Phon contour was derived and is shown in Fig. 4.[2]

2) Summation of loudness levels, i.e., the manner in which the loudness levels of several octave bands of noise heard simultaneously add up, was studied. The following semiempirical law of addition was discovered. The loudness level of N equally-loud octave bands of noise heard simultaneously is 20 log N dB greater than the loudness level of each band. Therefore, the voltage outputs from individual equally-loud bands should be arithmetically added (not as the root-mean-square) prior to application to a meter calibrated in decibels. If the sounds of the octave-band components have unequal loudness levels, this law of summation still is applicable, except for a small error when there are relatively strong low-frequency components in the presence of relatively weak high-frequency components.[7]

It is shown by Bauer and Torick[7] that the result of this method of addition is very similar to the results obtained with the semiempirical (but more complex) law of partial loudness addition of Stevens,[8] and embodied in the Proposed Loudness Standard.[6]

3) The ballistic characteristics of the ear for octave bands of noise were determined. This established how high the meter should read when subjected to a short, single, impulsive sound. This is shown in Fig. 5, together with that of a typical VI meter. It is seen that while the Loudness Monitor need not be faster than a typical VI for 0.3-s impulsive sounds, it should be considerably more responsive to shorter impulses.

VII. PRELIMINARY EXPERIMENTS WITH THE LOUDNESS MONITOR AND FURTHER INVESTIGATIONS

A first experimental Loudness Monitor in accordance with the projection described in the preceding section was built following the block diagram shown in Fig. 6. For the sake of circuit economy, the simplified averaged

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[1] "Pink noise" is a name used for Gaussian noise, the power spectrum level of which decreases at 3 dB per octave. Therefore, the band-pressure level per fractional octaves is constant with frequency.

[2] This average contour differs from the one shown in Bauer and Torick,[7] which was not as accurately determined as the present contour.

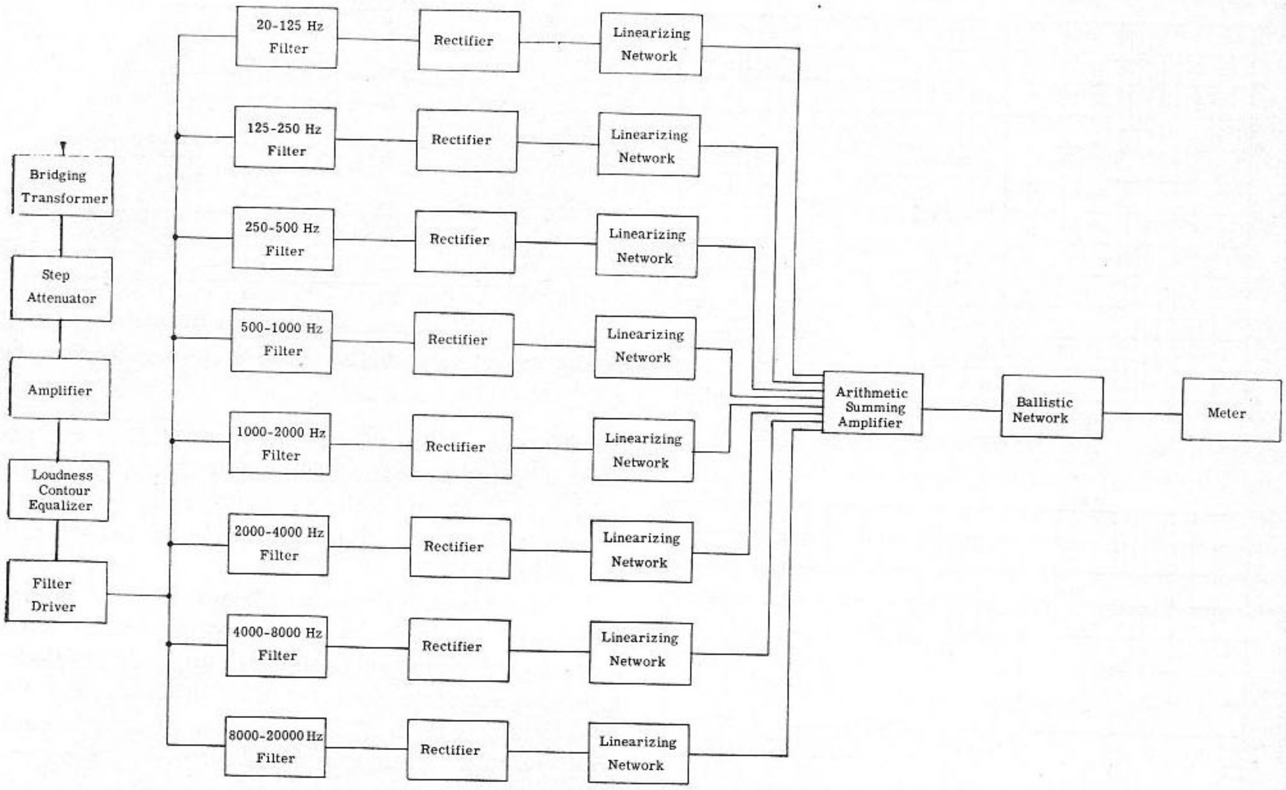

Fig. 6. Block diagram, proposed loudness monitor.

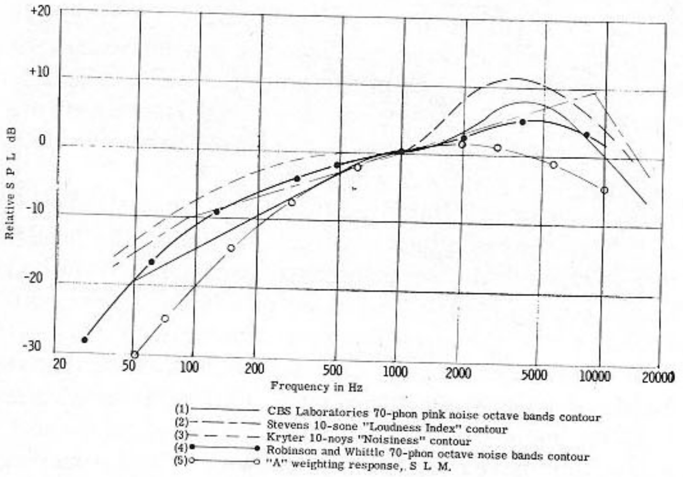

Fig. 7. Comparison of contours (inverted).

contour derived by Bauer and Torick[7] was adopted. The simplified contour did not exhibit the shelf at 1000 Hz evident in Fig. 4. The readings of the preliminary experimental Monitor did not correlate well with the loudness assessments of the psychoacoustic test panel. A number of modifications of contour were attempted, but it was finally determined that the use of the precise contour in Fig. 4 was needed to produce an optimum result. In addition, further investigation of ear ballistics appeared to be in order.

It is interesting to compare the CBS Laboratories average 70-Phon contour with the recent findings of other investigators. Of special interest are the equal "Loudness Index" contours of Stevens,[8] the "Equal Noisiness" contours of Kryter,[9] and the averaged contours of Robinson and Whittle.[10] These are shown in Fig. 7. It is seen that CBS Laboratories' 70-Phon average contour at low frequency is not too far from the contours of Stevens and of Robinson and Whittle, and at high frequencies it falls between the latter contour and that of Kryter. Possibly, this is because the CBS Laboratories teams of relatively naive listeners did not recognize the distinction between "loudness" and "noisiness."

VIII. Ear Ballistics for Repeated Pulses

It has been observed by previous investigators that repetitive sound pulses have a cumulative effect in human hearing which tends to enhance their loudness.[11] This effect was studied in a manner especially appropriate for the Loudness Monitor with the aid of our psychoacoustic team. The results are summarized in Table I.

A 900-ms pulse was used to establish the loudness level of 70 phons. Then, a 50-ms pulse of equal intensity was presented to the panel. According to Table I, the intensity of this single 50-ms pulse had to be raised 6.3 dB to equal the loudness level of the 900-ms pulse. This result is in conformity with that previously shown in Fig. 5.

Next, two 50-ms pulses spaced apart by 50 ms were studied. Their loudness level was found to be 4.3 dB less than that of the 900-ms pulse. However, when four or

TABLE I

LOUDNESS LEVEL OF PULSES IN 2 TO 4 kHz 70-PHON NOISE BAND

Pulse Length (ms)	Time off Between Pulses (ms)	Number of Pulses	Relative Loudness Level
900	—	1	0.0
50	—	1	−6.3
50	50	2	−4.3
50	50	4–10	−0.2 to +1.7 dB (+1.0 dB average)
50	100	7	−0.6
50	300	3	−3.6
50	300	10	−3.0
50	600	2	−4.3

more similarly spaced 50-ms pulses were presented, their loudness levels were judged to be on the average 1 dB greater than that of the 900-ms pulses.

In the next series of tests, repeated 50-ms pulses were spaced by increasing intervals of silence. It was noticed that as the time off was gradually increased, the loudness level again began to approach that of single 50-ms pulses.

The effect illustrated in Table I can be approximated electrically by suitable choice of the attack and decay time of the Loudness Monitor. A 0.1-s attack and 0.5-s decay time produce the required effect when used with a standard vu meter movement with the rectifiers removed. This choice of time constants does not reflect the loudness enhancement above the steady-state level. This latter effect is small and, in the initial model of the Loudness Monitor, did not appear to warrant the circuit complication required to implement it.

IX. TIME CONSTANTS FOR PROPER LOUDNESS LEVEL SUMMATION

A review was made of the method of obtaining the overall time constants of the Loudness Monitor. It was determined that the time constants employed in the adding network of the experimental model were too short to provide proper summation of the individual loudness components.

Through a series of tests it was ascertained that the summing time constant should be sufficiently long to properly add the various components of a sound appearing within a time frame of less than approximately 0.1 s. The desired meter action was achieved by dividing the function of the time constant between the summation network and the indicating instrument to conform with this rule. An attack time of 0.02 s, followed by a 0.20-s decay time in the summing network, followed by a 0.1-s attack time and 0.5-s decay time of the indicating instrument circuit, was found to be satisfactory for this purpose.

X. CALIBRATIONS

Since the Loudness Monitor has a "shaped" frequency response, the method of applying it to an audio circuit is to some degree arbitrary. For convenience, we have chosen the "0" reference level of the Loudness Monitor at 1000 Hz steady-state tone so that it is identical with that of a vu meter. During actual operation, the Monitor readings of course become modified by the frequency contour summation characteristic and the ballistics of the meter in accordance with the relative loudness level of the program. When monitoring a program, the readings of the Loudness Monitor are referred to as loudness level units (LU).

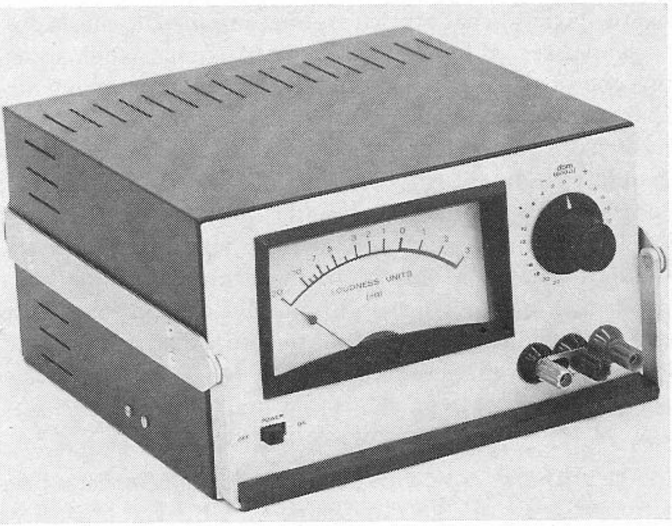

Fig. 8. Field-test prototype loudness monitor.

The scale calibration of the Loudness Monitor is equivalent in appearance to a VI scale. As with the volume indicator, a stepped attenuator is provided for adjusting the meter readings close to the "0" reference. The relative loudness level in LU is determined by adding the peak of the meter reading to the number marked on the attenuator dial. The field-test prototype Monitor is shown in Fig. 8.

XI. CONCLUSION

The Loudness Monitor appears to meet the requirements of the role assigned to it, i.e., to monitor correctly the loudness level of broadcast sounds under normal conditions of listening. During the development stage, several equal-loudness contours were tried, but the contour finally chosen as most appropriate is the CBS Laboratories pink noise, octave-band contour. When a number of octave-band sounds are present simultaneously, their loudness levels follow the law of arithmetic addition of normalized potentials corresponding to these loudness levels. Any such sounds appearing within a 0.1-s time frame are treated as simultaneous sounds. The ballistic characteristics of the ear for impulsive sounds have been represented by a rise time of 0.1 s and a decay time of 0.5 s.

As initial verification, listening with a high-quality loudspeaker system, typical speech and musical sounds