An acoustics measurement program for evaluating auditoriums based on the early/late sound energy ratio

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The importance of the early reflection portion of a sound decay process in an auditorium is well established. Curves showing early/late sound energy ratios (ELR) in the early reflection period comprise a useful way of examining energy-time data within that period. An auditorium measurement and analysis procedure using ELR data in the period between 20 and 200 ms after the arrival of the initial signal is presented.

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INTRODUCTION

The importance of the early reflection portion of a sound decay process in an auditorium with respect to degree of clarity and nature of reverberant and spatial effects is well-established.[1–4] A variety of ratios utilizing direct, early, and late sound energy have been produced to quantify room acoustic qualities relating to both clarity and reverberance, the most familiar probably being C_{50} and C_{80} for speech and music clarity, respectively. Numerous studies have shown good correspondence between early/late ratios (ELR) and other acoustic measures such as early decay time (EDT), center time (t_s), articulation index (AI), and speech transmission index (STI).[5–7]

One need not be limited to obtaining an ELR value at a particular dividing time, however, and curves showing ELR values throughout the early reflection period comprise a useful method of examining energy-time data in that period. An automated measurement and analysis program has been created to acquire energy-time data and produce ELR curves for the period between 20 and 200 ms after the arrival of the initial signal. The ELR measurement and analysis concept and procedure is discussed in this paper, with examples of data collection and analysis included for illustration.

Beyond those already noted, additional contemporary objective measures of room acoustic quality include interaural cross-correlation coefficient (IACC), strength (G), lateral fraction (LF), and reflective energy cumulative curve (RECC).[8,9] ELR information tells nothing about IACC and G. The difference between lateral-ELR and omnidirectional-ELR values (in dB) should correlate well with LF vs time values. RECC is equivalent to the numerator of a without-direct-signal early/late ratio.

I. MEASUREMENT CONCEPT

To interpret the acoustic response of an auditorium on the basis of measured data, one might logically first turn to the highly detailed information contained in a thorough set of energy-time measurements. Energy-time curves (ETC) by themselves are somewhat difficult to comprehend, though, at least from the standpoint of allowing one to imagine the subjective response at a particular location by merely examining the curves obtained at that location. Consequently, various operations, processes, etc., are desired to give more meaning to the curves and to facilitate interpretation. To illustrate with a well-known example, the Schroeder curve which results from summing energy backwards in time from t_f to t_o—shown in Fig. 1 above the ETC—is clearly a very helpful process for establishing the decay rate of the associated ETC.[10]

The perceived acoustic response of a space is critically influenced by the details of the energy-time response in the early portion of the sound-decay process. One useful way of examining energy-time data in that early period (which could be said to extend beyond the arrival of the initial signal from 150 to 200 ms) is to examine early/late sound energy ratios within that period. The principal advantages afforded by this format are: (1) A ratio normalizes the data so that only reverberation time (RT) and relative strength of the direct signal remain as the controlling theoretical parameters, assuming simple diffuse-field theory. This allows theoretical curves calculated with these parameters to be used as comparison curves for observing deviations between measured and idealized behavior. (2) Established clarity measures for both speech and music exist for the 50 and 80 ms ratios (C_{50} and C_{80}).

A. ELR curves

Figure 2 shows several ELR curves. The upper measured curve shows ELR values (expressed in dB by taking the logarithm of the ratio) containing the energy of the direct signal (C_t), and the lower measured curve shows ELR values with the energy of the direct signal omitted (C_{to}). The observed difference between the two measured curves, C_t and C_{to}, gives an indication of the relative strength of the direct signal. Another curve, C_x, shows theoretical ELR values for a pure exponential decay based on a decay time equal to that of the measured curves

$$C_x = 10 \log(e^{13.82t/RT} - 1), \tag{1}$$

where t is the ratio dividing time in seconds. This is the theoretical equivalent of the measured without-direct-signal curve, C_{to}, and can serve as a useful reference. For this purpose, the difference between C_{to} and C_x is illustrated by a fourth curve produced by subtracting one from the other. Since C_{to} is solely a consequence of room effect, this differ-

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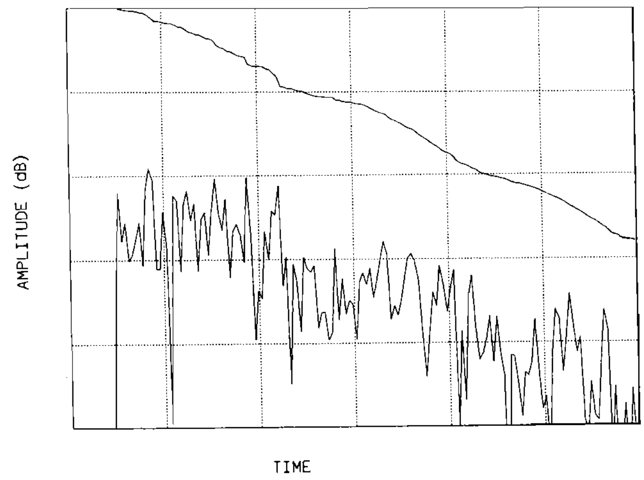

FIG. 1. Energy-time curve with Schroeder integral.

ence curve clearly illustrates reflective behavior in a comprehensible and meaningful manner.

Simple diffuse-field theory predicts no variation in sound level once one has moved beyond some critical distance and into the reverberant field. In auditoriums, however, levels generally do continue to decrease with increasing distance from a source, and Barron has presented a "revised theory" to more accurately predict sound level variations in auditoriums.[11] Total absorption (which can be expressed in terms of room volume and RT), and source/receiver distance are also considered in this revised theory. The possibility exists, then, to produce a "Barron" curve (C_B) to use as a theoretical equivalent to C_t. (See Fig. 3.) The exponential curve, C_x, and the Barron curve, C_B, differ only by including in the latter the ratio of direct-to-late energy, expressed in terms of distance, room volume and RT:

$$C_B = 10 \log\left(\frac{Ve^{(0.04r+13.82t)/RT}}{312RTr^2} + e^{13.82t/RT} - 1\right), \qquad (2)$$

where V is room volume in m^3, r is source–receive distance in m, and t is in seconds.

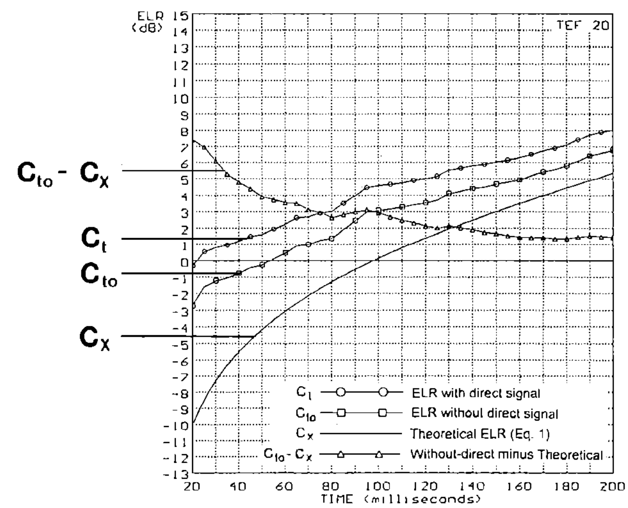

FIG. 2. ELR data curves.

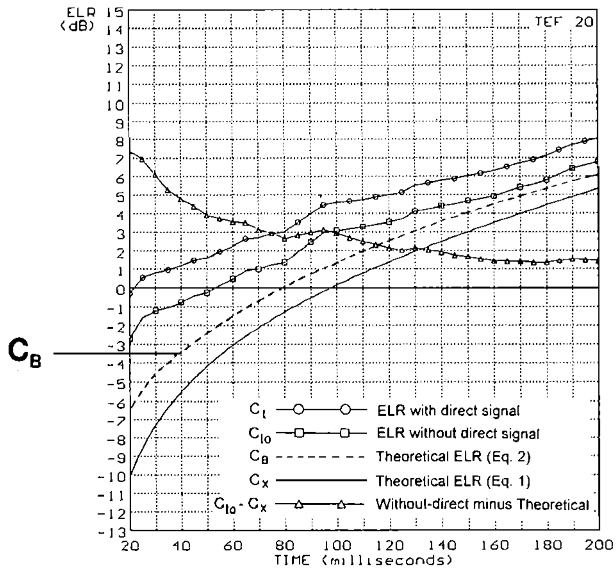

FIG. 3. The C_B curve added to display of Fig. 2.

One should understand, though, that neither theoretical curve is being presented as an "ideal acoustic response" curve. Rather, the theoretical curves are used to serve as baselines for comparative purposes, and, with that in mind, one is left with the question of which of the two might better serve this function. In this paper, the exponential-decay (or, diffuse-field) curve has been used more extensively. In part, this is because only a single parameter (RT) is required, since in many measurement situations the volume of a space is not readily available information. The measurement software used was written so that ELR processing requires only RT and source–receiver distance, both of which are supplied by the measurement itself.

Realizing that C_t and the associated C_{to} differ only by a constant quantity in the numerator of the ratio representing the energy of the direct signal, use of the exponential curve as a reference for C_{to}, along with observation of the degree of separation between the two measured curves provides one with insight to both early reflection behavior and relative strength of the direct signal. Of course, one need not be limited to using only one or the other of the two theoretical curves, and the author considers C_B as a useful supplement to C_x.

B. ELR and the early reflection period

In large rooms, for which this measurement procedure is intended, one can say that the decay process consists of the direct sound; followed by early reflections that extend out for as much as 200 ms or so; and then the late or reverberant sound (Fig. 4). (Mean-free-path considerations dictate that the point chosen for transition from early to reverberant sound is directly related to room volume.[12,13]) The early/late ratio is influenced by all of these components, and the ELR measurement procedure is particularly concerned with the early reflection period between 20 and 200 ms, which plays such an important role in establishing a room's character with respect to clarity, reverberance, and spaciousness. Clarity and reverberance are generally considered to be largely

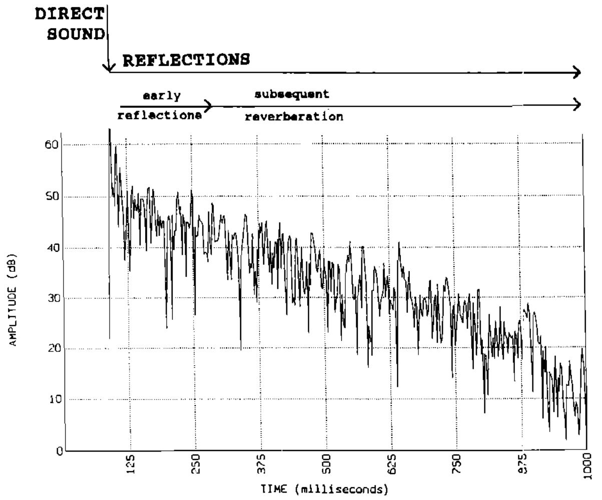

FIG. 4. Energy-time curve with principal components.

reciprocal qualities. (For example, a reciprocal form of C_{50} is called "running liveness" (R), and is intended as a measure of reverberance.)[14] The qualities encompassed by the term spaciousness depend on the directional characteristics of reflected energy, in addition to the details of arrival time, strength and frequency upon which clarity and reverberance are most dependent. (Note, however, that direction of arrival cannot be completely separated from clarity and reverberance since signal detectability changes with direction.)

The 20 to 200 ms early reflection period might be further divided into early–early and late–early categories (Fig. 5). These categories cannot be defined with precision since, among other things, they vary with room size, RT, strength, spacing, and direction of reflections, and type of activity (for example, speech versus music, or organ versus piano). In simple terms, reflections arriving within the first 50 ms will usually contribute beneficially to speech clarity, those within 50 to 100 ms may or may not be beneficial, and those arriving subsequently will probably not contribute to clarity and may instead be harmful. For music, these useful/harmful

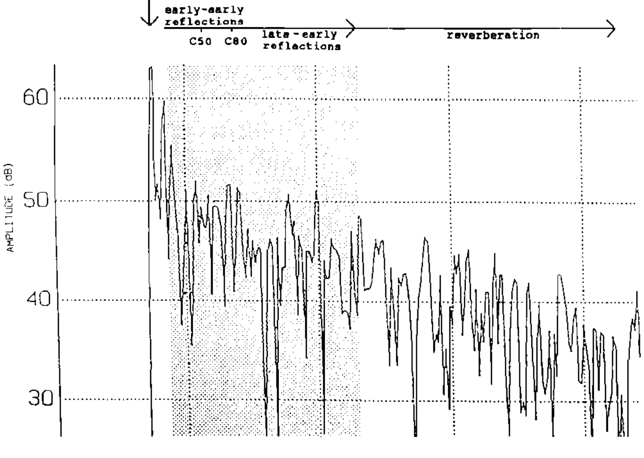

FIG. 5. Early portion of energy-time curve showing ELR calculation period (shaded).

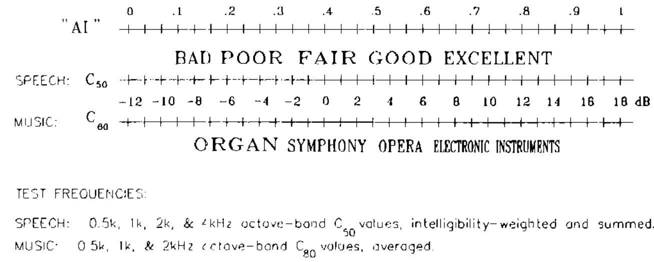

FIG. 6. AI relationship to proposed speech C_{50} and music C_{80} rating scales.

times can be extended some, as a generalization, although this is a variable that depends on type of instrument, tempo, scoring, compositional style, and so forth. Different integration-time intervals are used for the speech and music clarity ratios, C_{50} and C_{80}, for this reason, of course.

C. ELR and proposed frequency averaging for speech and music

Frequency is an everpresent variable in acoustics, and must be fully considered in the acquisition and analysis of data. In room-acoustics analysis, the specific interest may be speech, music, or both. The frequencies important to speech intelligibility have been well-defined,[15] and the ELR procedure for speech-acoustics analysis employs the weightings associated with intelligibility contribution as a function of frequency band. Specifically, in this paper, "speech" values come from the energy-time data in the 0.5, 1, 2, and 4 kHz octave bands, with respective intelligibility contributions of 15%, 25%, 35%, and 25%. Therefore, the so-called speech curve is produced by multiplying the "C" values (in dB) within the four individual frequency bands by their associated weighting fractions, then summing to obtain the composite values.

For music, there is no such clearly defined set of contributions for clarity as a function of frequency, nor can there be in view of the large variety of musical instruments and musical styles. Merely on the basis of listening to filtered octave bands of recorded music, the 0.5, 1, and 2 kHz bands were tentatively selected as the ones of greatest importance to clarity, and the "music" curve is produced by summing the C values (in dB) of those three bands, then dividing by 3. The author's use of those three bands is not unique, at least for C_{80},[16] but there has been disagreement with this choice, and it may be that a more refined music composite will evolve.[17]

D. Speech C_{50} and music C_{80} rating scales

Figure 6 illustrates a proposed speech intelligibility rating scheme for C_{50} which assumes that the early/late ratio may be viewed as a useful/harmful energy ratio, and, as such, can be equated to a long-term rms speech-signal-to-noise ratio. C_{50} can then be transposed to articulation index (AI). AI values, which range from 0 to 1, represent the intelligibility portion of a speech signal received by a listener, and are based on a speech dynamic range of 30 dB, with a 12-dB long-term rms to peak characteristic.[18] The AI fraction, therefore, is calculated by adding 12 dB to a long-term rms signal/noise ratio, and dividing that by 30 dB. By using C_{50} as the signal/noise ratio, a rating scheme can be applied, as is commonly done for AI, as shown in Fig. 6. The process here follows from French and Steinberg's[19] original development of AI using a signal/noise concept, and Lochner and Burger's[20] subsequent use of speech energy for both the effective signal and masking noise portions as a way of predicting the effects of reflected energy on intelligibility scores.[21] The C_{50} rating scale of Fig. 6 has not yet benefited from extensive use, and some adjustment may occur over time.

With respect to music, a C_{80} of 0 dB plus or minus 2 dB has been pretty well established as a good range for symphonic music.[22,23] A proposed extended rating scale for C_{80} is shown in Fig. 6, along with the C_{50} scale used for speech. The music scale is merely an extrapolation based on Reichardt's[24] assertion that the optimal C_{80} value for symphony orchestra is centered around 0 dB. The C_{80} scale is intended only for full-size performance spaces (not small recital halls, small churches, or orchestra rehearsal rooms, for example).

II. MEASUREMENT PROCEDURE

The ELR measurement procedure can be summarized as follows:

1. A series of ETCs are obtained at octave intervals, including at a minimum the 0.5, 1, 2, and 4 kHz bands.

2. From the ETCs, ELR values are computed and plotted every 5 ms in the period between 20 and 200 ms after the arrival of the direct signal to produce C_t.

3. A second set of ELR values is computed with the energy of the direct signal omitted to produce C_{to}. For this, a delayed calculation starting time is used, and the amount of delay is intended to roughly correspond to what one would expect to use to bypass the direct signal on an ETC. Specifically, the ELR software omits 6, 7, 8, and 9 ms, respectively, for the 4, 2, 1, and 0.5 kHz bands. (Increasing times are used with decreasing frequency in deference to decreasing resolution.)

4. A theoretical C_{to} curve, C_x, is computed on the basis of RT [Eq. (1)], and is shifted on the screen by an amount of time corresponding to that used to omit the direct signal for C_{to} so that C_x will be time aligned with C_{to}. (Since the purpose is for use as a matching curve, absolute values are of less interest than best-match values. For example, if 6 ms have been omitted to produce C_{to}, the resulting curve has a delayed calculation starting time, but that delay is overlooked so the curve may remain aligned with the corresponding C_t. The matching curve, C_x, is then similarly shifted. In this example, the C_x value shown on the display for 100 ms would be the calculated value for 94 ms. One consequence of this shift is to increase by a small amount the separation between C_t and C_{to}, and between C_B and C_x.)

5. A difference curve is produced by subtracting the theoretical C_x from the measured C_{to}.

6. In addition to the curves associated with each measurement, two sets of averaged curves are produced—speech and music—as a way of usefully consolidating the large quantity of information obtained by measuring at several octave-spaced intervals. (These frequency-averaged curves were defined in Secs. I C and I D).

7. Optionally, a theoretical C_t matching curve, C_B, may be calculated on the basis of Barron's theory of level-versus-distance in auditoria [Eq. (2)]. This calculation requires knowledge of the auditorium's volume in addition to RT and source–receive distance. (RT and source-receive distance are supplied by the measurement software used by the author.)

A. Instrumentation

All measured data used in this paper were acquired with Techron TEF-20 instrumentation with commercially available ELR software specifically designed to accomplish the first six listed functions. In those instances where Barron curves are shown, the values have been calculated separately and added to the ELR display. For the tests described in the following section, a 20-cm (8-in.)-diam dodecahedron loudspeaker with twelve 9-cm ($3\frac{1}{2}$-in.) drivers was used to produce the test signal, and a B&K type 2225/WH1013/WH1126 compact sound level meter with 1.3-cm ($\frac{1}{2}$-in.) condenser microphone was used to receive the test signal.

The dodecahedron loudspeaker's omnidirectionality was desired for analysis of music acoustics. For maximum precision in speech acoustics analysis, however, a loudspeaker that more closely represents the directional characteristics of the human voice is preferable. An omnidirectional source might underrate speech clarity values in the front half of a room by 2 to 3 dB. Using as an example the auditorium discussed in the followed section, the insertion of a speech directivity factor, Q, of 2.5 into the first term of Eq. (2) (the direct-signal term) results in a calculated C_{50} value increase at position 1 from -2 to -0.4 dB. If both the source–receive distance and RT are reduced by half, the respective values become 5 and 8 dB.

III. MEASUREMENT RESULTS AND ANALYSIS

The ELR measurement procedure provides RT and the clarity measures, C_{50} and C_{80}. These parameters are fundamentally important in characterizing an auditorium's acoustics, and appropriate values are fairly well established, but these single-number parameters are not sufficient to give a full characterization. The curves provided by the ELR procedure can greatly supplement the characterization by providing (1) details of the early reflection process, and (2) knowledge of the relative strength of the direct signal. Analysis of ELR data will be demonstrated briefly in this section by looking at just the main content of several examples. (The author wishes to stress here that the purpose of this paper is to present a new method of analyzing, or examining, impulse response information. The hope is that new knowledge will result from the ELR procedure with time. The auditorium discussion that follows is included to demonstrate the measurement procedure and nature of data obtained. Relationships drawn between subjective and objective information are only intended to be suggestive.)

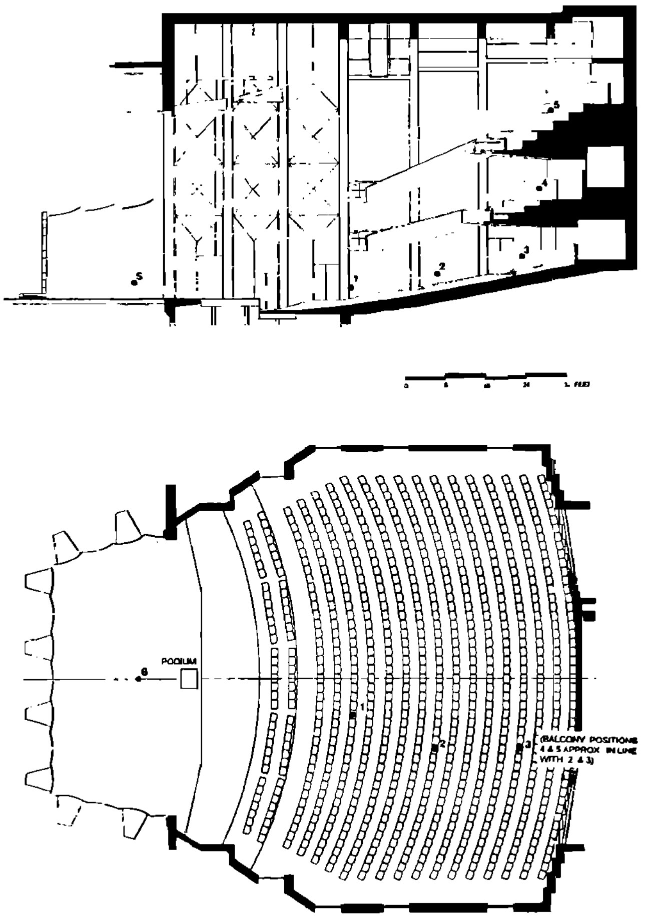

FIG. 7. Auditorium plan and section showing source and receive test locations.

A. Test auditorium

ELR measurements were made in a 1300 seat multipurpose auditorium equipped with a standard set of commercial stage enclosure towers and batten-hung ceiling panels for changeover to the concert hall function. Measurements were made with the enclosure in place and the stage setup with chairs and stands for a full symphony orchestra. The orchestra's chairs and stands were arranged on the main stage fully within the enclosure, but the pit lift was positioned at stage level and formed a large, bare forestage surface. Upstage instruments were placed on risers.

The auditorium experiences primary use as a university and community facility, and experiences supplementary use as a commercial recording facility, with some major New York performing groups among those recording there. All interior boundaries are hard-surfaced, and the principal suspended sound-reflecting element in front of the proscenium is "wrinkled" to scatter some sound laterally. The design dates to about 1970.

The auditorium is roughly square in plan, and has two balconies. Figure 7 shows an auditorium plan and section with test locations. Only a single test source location was used, and this was on stage-centerline, 4 m (13 ft) from the edge of the main stage, 3 m (10 ft) beyond the podium between the second violin and viola sections, and at a 1-m height, which roughly corresponds to that of a seated player's instrument. In the concert hall configuration without audience, the midfrequency RT is 1.9 s. Subjective judgments at each test location were made by the author at a rehearsal of a high-quality professional symphony orchestra with no audience present, and this occurred prior to acquiring ELR data. Subjective descriptions are limited to string sound and overall orchestral sound since only a single source location was used, and this was within the string section.

B. Subjective analysis

The author judged the auditorium's acoustics for symphony orchestra to be reasonably good everywhere, but not outstanding anywhere. The unoccupied hall's mid-frequency RT of 1.9 s would seem plentiful for concert hall acoustics, but the hall sounds less reverberant than this and does not produce an expansive, well-enhanced, homogeneous response. The strings are never fully rewarded for their efforts, as their sound never completely develops into a full-bodied, well-blended entity (or, using other descriptive jargon, "never blossoms into a glowing symphonic sound"). Some shrillness of string sound is characteristic, but the degree varies with listening position. Clarity for music is good everywhere, but room sound (reverberance and spaciousness) is generally weak.

At position 1 (front-orchestra, 13.1 m from source), the sound is good but not unified and well-blended; the sound is loud, but without much audibility of room sound.

At position 2 (middle-orchestra, 18 m from source), the sound is loud, but is somewhat "dry" and has little room sound.

At position 3 (rear-orchestra, 23.5 m from source), the string sound is much fuller, less shrill, and more homogeneous, though not fully blended into a totally unified sound. One of the best listening locations in the hall.

At position 4 (1st balcony, 25 m from source), the sound is expansive, the strings are less shrill, and there is a good deal of intimacy. One of the best listening locations in the hall.

At position 5 (2nd balcony, 26.8 m from source), the most expansive and homogeneous room sound is produced, but strings are quite shrill; most exciting sound in hall, but a "table-radio" quality causes it to be less good than at positions 3 and 4.

C. ELR analysis

Figure 8 shows the 0.5, 1, and 2 kHz averaged ELR data for the five positions. C_{80} values include the direct signal, and are music composites as discussed in Sec. I C. Direct-signal information is not included in the difference curves, as discussed in Sec. I A. The dominant features of the measured data can be described as follows.

For position 1 (Fig. 8-1), the direct signal is strong in relation to subsequent reflected energy, as indicated by the large separation between C_t and C_{to} (and as one would expect at this short distance, especially with the bare forestage surface); weak room-reflection contributions are indicated by

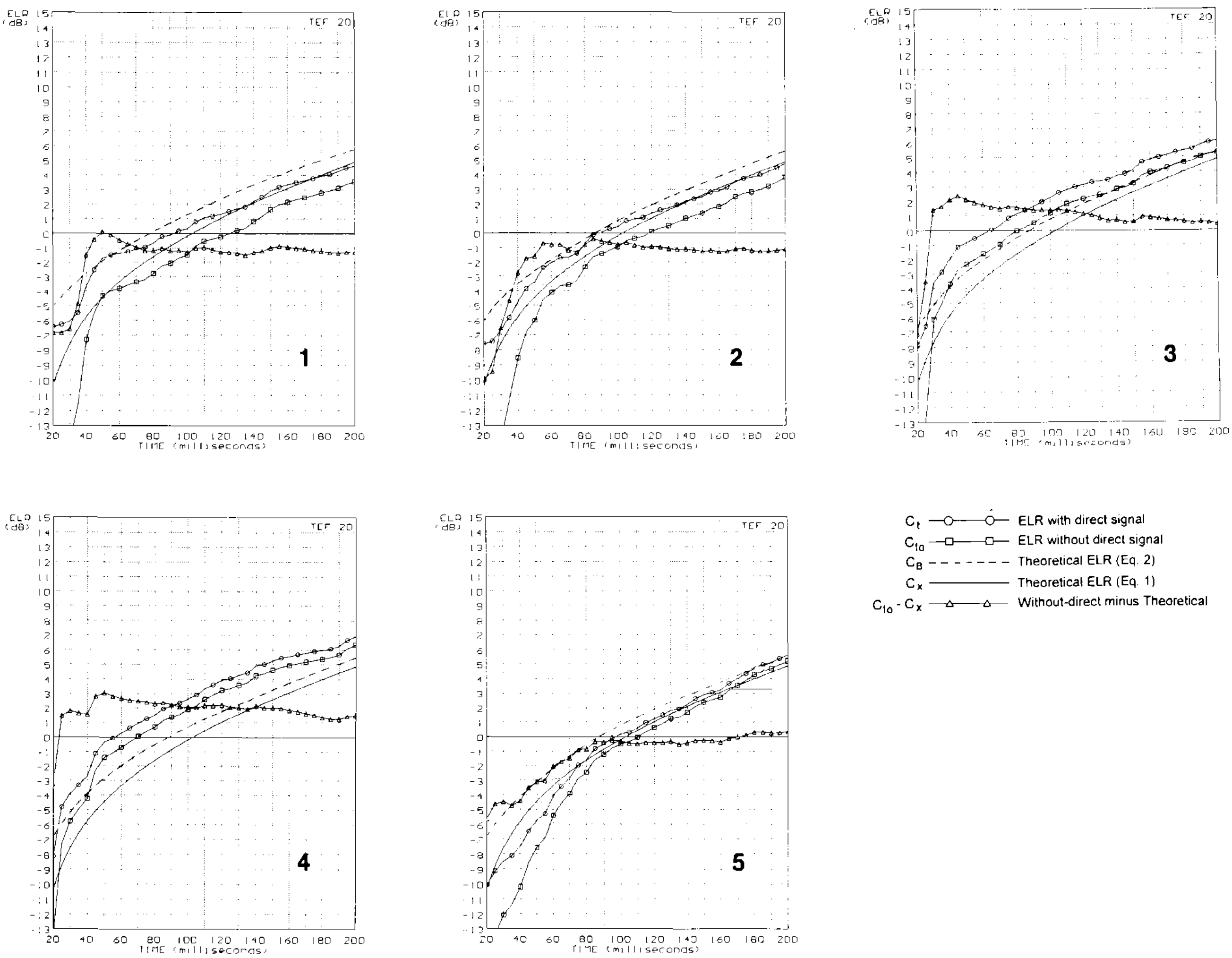

FIG. 8. Average 0.5, 1, and 2 kHz ELR data at 5 audience locations.

the negative values of the difference curve, especially in the first 40 ms; a reflected-energy peak on the difference curve occurs around 50 ms. $C_{80}=-0.6$ dB.

For position 2 (Fig. 8-2), a relatively strong direct signal is indicated by the large initial separation between C_t and C_{to}; a large deficiency of early reflected energy is seen in the first 45 ms; a peak value on the difference curve occurs in the late–early period between 80 and 90 ms. $C_{80}=-0.7$ dB.

At position 3 (Fig. 8-3), a strong initial-time-delay arrival (t_I)[25] occurs in the 25 to 30 ms interval, after which the difference curve remains positive because of significant additional early energy arrivals. $C_{80}=1.1$ dB.

At position 4 (Fig. 8-4), the direct signal's relative contribution is weak in conformity with the 25 m distance (compare the degree of separation between the two measured curves and between the two theoretical curves); a strong t_I shows at 25 ms, with a continuing series of early arrivals maintaining positive difference-curve values; a strong reflected energy peak on the difference curve occurs at 45–50 ms. $C_{80}=1.5$ dB.

At position 5 (Fig. 8-5), the relative contribution of the direct signal is small in conformity with the 26.8 m distance to the source; the difference curve is negative, and most noticeably so in the early–early period between 40 and 70 ms (this runs counter to the expectation of many short-delay arrivals in a rear top balcony). $C_{80}=-1.6$ dB.

Without straining to interpret a strict correspondence between the subjective and objective descriptions, it is nevertheless clear that the best listening positions, 3 and 4, are richer in early energy (as evidenced by positive-valued difference curves), and have small t_I values. (In this paper, t_I has been determined by examination of difference-curves, rather than ETCs.)

The C_{80} values are consistent with the observation that clarity was good at all locations. The lowest C_{80} value occurs at position 5, which was described as having the most expansive sound quality (though not the best). Just on the basis of expected change in RT, these values should increase about 1 dB in the fully occupied hall (although the change to occupancy is a change that affects more than just RT, of course, since the geometry of occupied seats is quite different from unoccupied seats, particularly with respect to grazing incidence sound energy).

Only composite 0.5, 1, and 2 kHz averaged curves have so far been examined. Figure 9 shows the curves associated with the four center frequencies of 0.5, 1, 2, and 4 kHz at a single position. Significantly, only positions 3 and 4 produced difference curves for most frequencies which turned

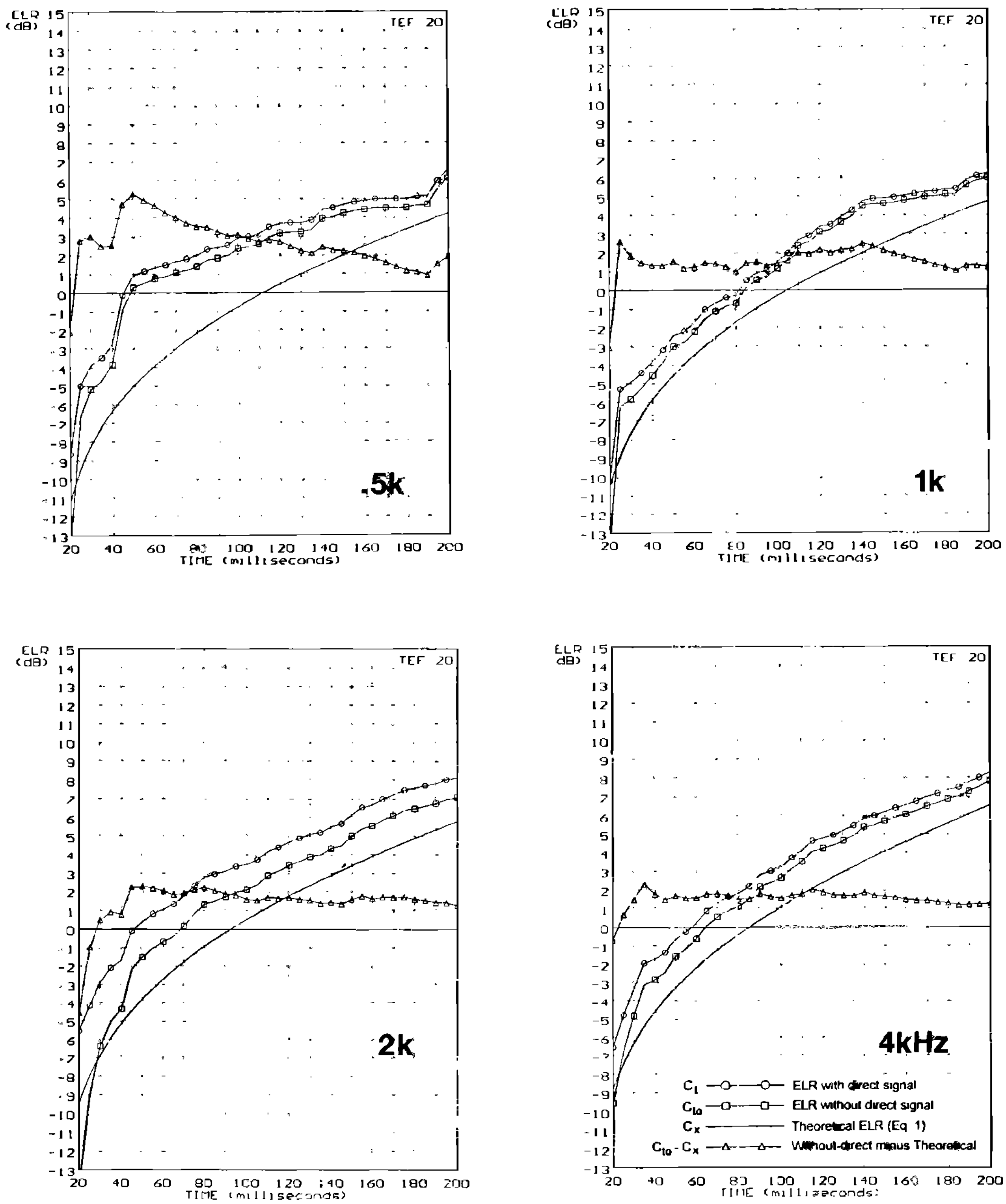

FIG. 9. Position 4 ELR at 0.5, 1, 2, and 4 kHz.

strongly positive after a short t_l. At position 5, large deficiencies were present in the early–early period in all but the 4 kHz band, and this might relate to the unpleasant sound quality described for that position if, in fact, those characteristics cause an increased prominence of high frequencies.

D. Influences on relative strength of direct signal

Of the two variables contained in Eq. (2)—distance and RT—distance more strongly affects separation between C_B and C_x than RT does within a hall (RT changes with frequency, of course). Source directivity is not included in Eq. (2), though, and, in fact, source directivity can strongly influence the separation between the two curves, as demonstrated earlier in Sec. II A. Just as the influence of the direct component is greatest at shorter distances and shorter RTs, so is the influence of "Q" when it is added to the direct component of Eq. (2). The issue of directivity is relevant since instruments have directional characteristics, though considerable scattering can result from the large quantity of chairs, bodies, and stands onstage. As a rule, directivity will increase and RT will decrease with increasing frequency, giving more prominence to the direct signal. Violins, for example, radiate energy very strongly forward (perpendicular to the fingerboard) and upward at higher frequencies, and one would not expect this radiation pattern to be inconsequential.

E. Further comments

After presenting the preceding set of subjective descriptions and corresponding measurements to illustrate ELR data and analysis, the author cautions against drawing interpretative conclusions too readily. Only with time and experience

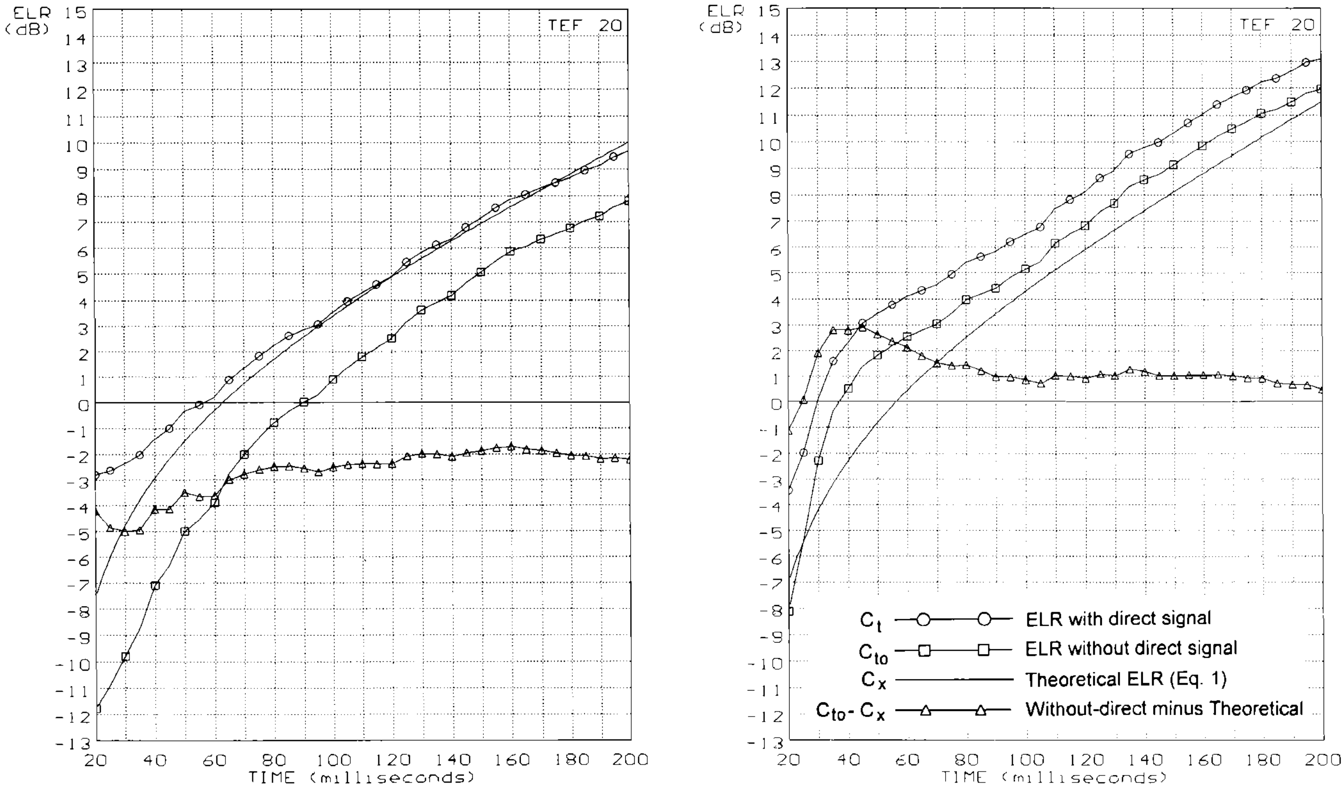

FIG. 10. Before (left) and after (right) speech-weighted ELR in renovated theater showing improvement in strength of early reflections at a middle-audience location.

will meaningful and accurate interpretations of data be assured, and it is much too early to know the ways and extent to which ELR data may prove to be useful. At the time of writing, the author had obtained many hundreds of measurements in at least two dozen spaces. However, a very large number of variables are involved since the measurements were made in a wide variety of room sizes, shapes, and reverberation characteristics, and, in these circumstances, interpretative conclusions on the basis of hall-to-hall comparisons are no more than tentative and uncertain, at best.

One of the attributes of the ELR procedure is its sensitivity, as should be apparent from the measured data already shown. As a further example, Fig. 10 shows before-and-after measurements performed in a small theater which underwent a very modest, mostly cosmetic renovation. Acoustic changes included improved ray diagramming from suspended sound-reflecting panels and some side wall reorientation. The difference curves of Fig. 10 clearly show the resulting improvement in early sound reinforcement.

Sometimes, measured and theoretical curves agree very closely throughout a space, while at other times, large variations occur not only between theoretical and measured data, but also between two test locations only a short distance apart (see Fig. 11). One assumes that the large deviations are full of meaning, and often the reasons appear obvious, but, again, much, or most, remains to be learned. At this early stage, the author believes three distinct difference-curve shapes will come to be identified with specific concert hall acoustic characterizations. The three are: (1) a sagging curve with high initial value (see Fig. 11, bottom right), (2) a gradually building curve with low initial value (see Fig. 11, upper-right and Fig. 8-5), and, (3) a flat curve that jumps up quickly to a strong value and remains close to that value (see Figs. 8-3 and 8-4). The desirability of one or another of these ELR characteristics will probably be different in large halls than in small halls because of loudness, signal detectability, and reflection-spacing differences. For large-hall music acoustics, the first listed curve-type will possibly be regarded as the poorest because of the weak early reflection sequence it portrays.

Another level of ELR analysis would be to obtain ELR with directional pickup and with binaural pickup. The difference between lateral ELR and omnidirectional ELR is an obvious comparison to explore, for example. This has not been done yet, but may prove interesting.

IV. ELR MEASUREMENTS AND SOUND SYSTEM PERFORMANCE

One very practical use for the ELR procedure is to objectively judge sound-system performance. Speech curves obtained with a room's sound system both on and off readily show the change in early energy and C_{50} values effected by the reinforcement system. (See Fig. 12.) ELR measurements may be obtained through sound-reinforcement systems in two ways. First, and most directly related to actual sound system usage, is to place the ELR test loudspeaker at the talker's position in front of a live reinforcement system microphone. With this procedure, one must make certain that the reinforcement system's level is predominant. This can be

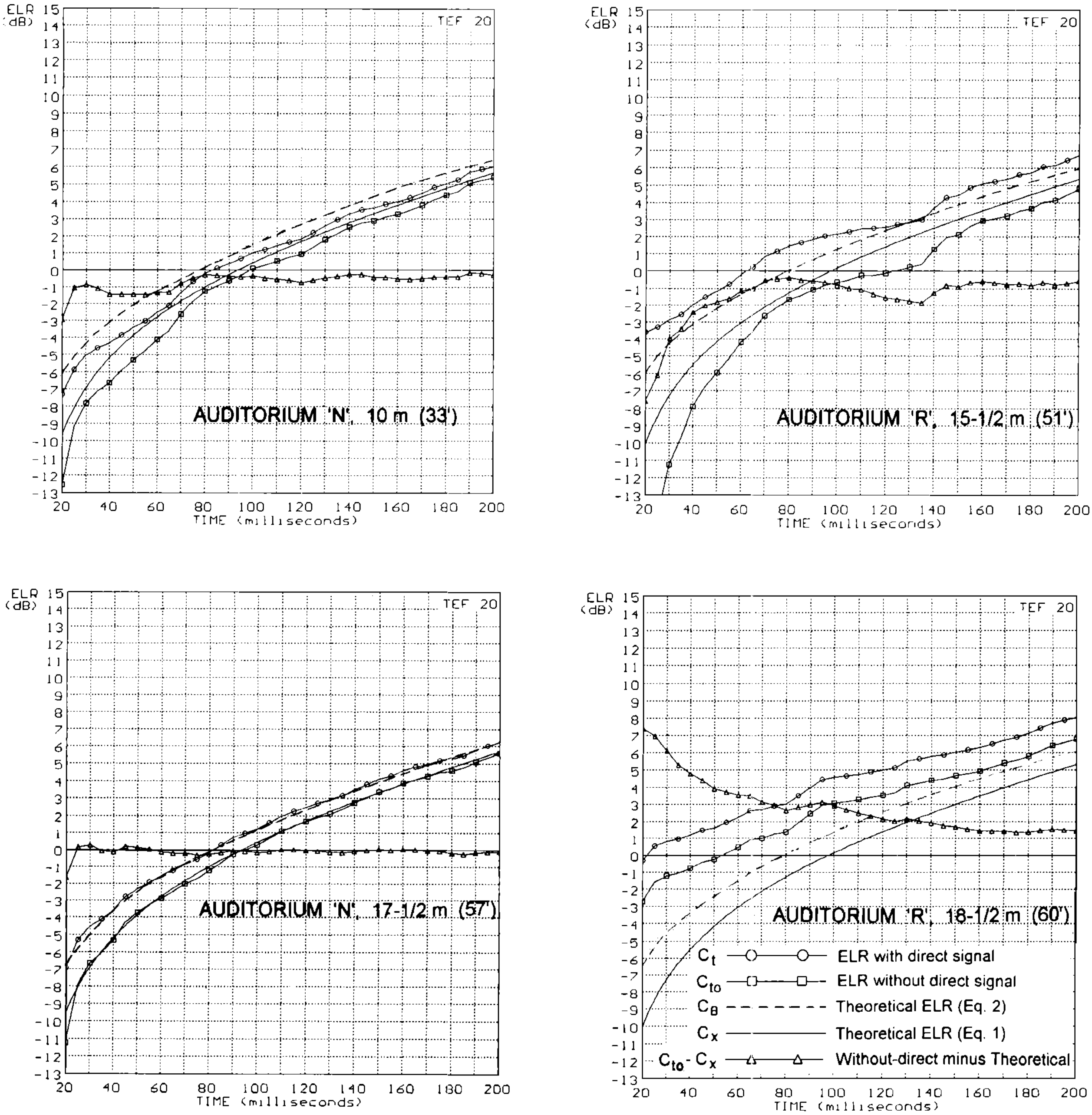

FIG. 11. ELR in 2 small auditoriums showing, on the left, good correspondence with theoretical curves at 2 widely spaced locations; and, on right, deviations from theoretical and from position-to-position with only 3-row separation. (Notice the difference curves, in particular.)

determined either by listening or by checking signal strength of the reinforced sound and its time-of-arrival on an ETC. A variation would be appropriate in rooms where sound from the person talking and sound from a distant reinforcement loudspeaker combine to give degraded intelligibility because of the poorly synchronized live and amplified sound components. In such cases, somewhat equal signal levels at the receive position from the reinforcement and test loudspeakers could be used.

The alternative method for measuring a sound reinforcement system is to patch directly into the system, omitting the ELR test loudspeaker and bypassing reinforcement system microphone pickup. Possibly worth clarifying in Fig. 12 is an apparent discrepancy in source-receive distances for the two measurements. There was no change in receive position, but when the sound system was turned on, the source position changed from the lectern to the nearest loudspeaker, which in this instance was a distributed loudspeaker at a 5.5-m (18-ft) distance.

V. SUMMARY

A measurement and analysis procedure based on the early/late sound energy ratio has been presented as a potentially useful way of evaluating the acoustic response of auditoriums. The ELR procedure described in this paper was developed for evaluating the acoustics of large spaces (such as auditoriums, concert halls, theaters, churches, arenas, and so forth), and the performance of sound systems within those spaces. Two measured ELR curves, one including and one

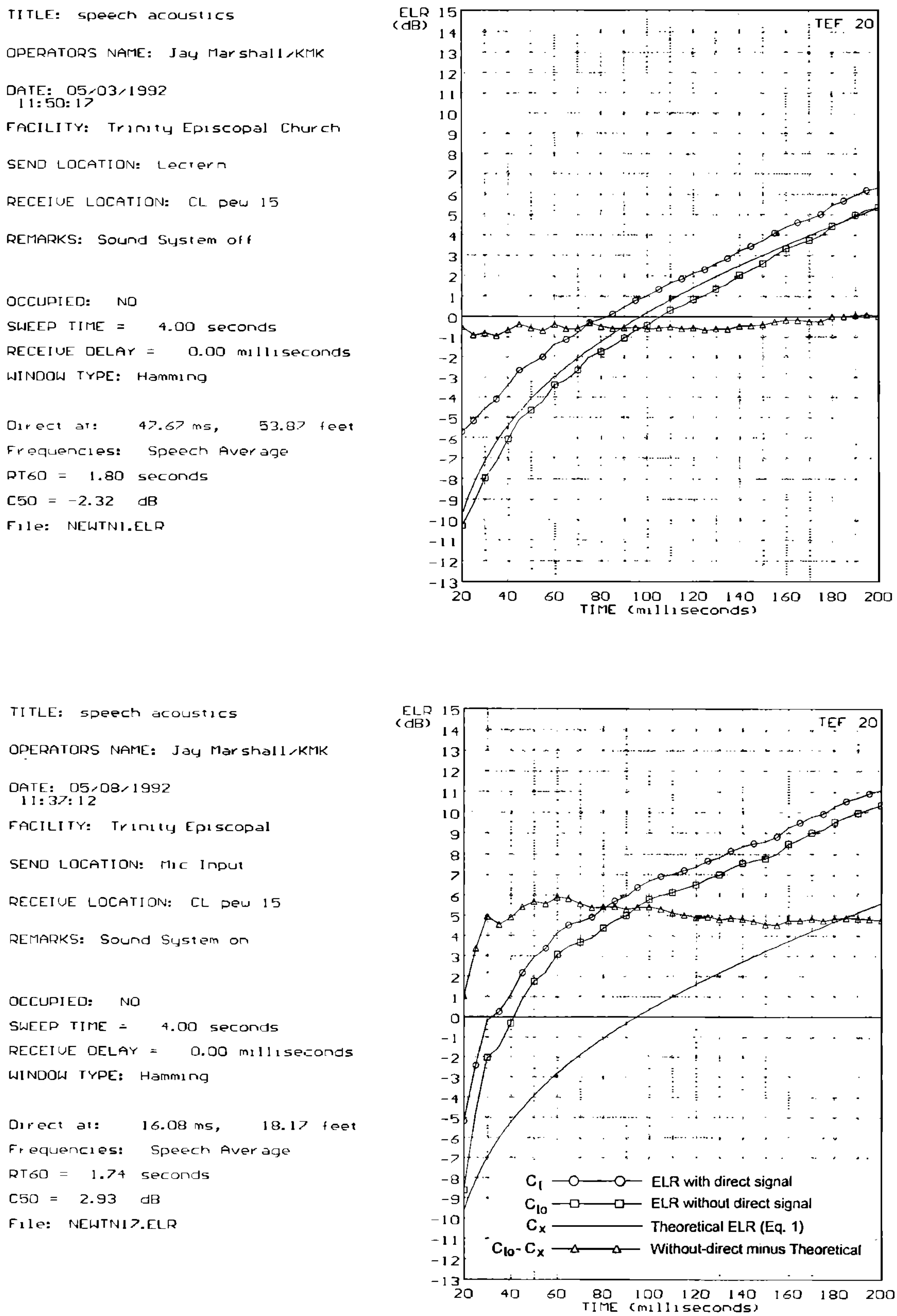

FIG. 12. ELR with sound system off (top) and on (bottom).

omitting the direct signal (C_l and C_{lo}, respectively), are displayed for the early reflection period between 20 and 200 ms after the arrival of the direct signal. Two curves based on diffuse-field theory, one with and one without the direct signal (C_B and C_x, respectively) may be used for comparison with their measured equivalents to assist in interpreting energy-time response in that period. The early reflection period is critically important since the subjective character of an auditorium's acoustics is largely established within that brief window of time. The difference curve, C_{lo} minus C_x, is especially useful in showing the significance of energy arrivals in that period. The principal audible effect of reverberation beyond the early reflection period is the persistence of sound heard during rests and separations between notes. None of this is to suggest, however, that ELR by itself can provide knowledge of all early reflection subjective effects.

The clarity measures C_{50} and C_{80} are also supplied by the procedure, including calculated composite frequency-weighted values using speech and music clarity frequencies as proposed by the author. Proposed subjective rating scales for the composite C_{50} and C_{80} values are shown in Fig. 6.

In sum, the ELR procedure provides: (i) The clarity measures C_{50} and C_{80} in individual octave bands, and in frequency-averaged and weighted forms; (ii) The behavior and relative strength of reflected energy in comparison with idealized exponential decay in the period between 20 and 200 ms after the first arrival, as indicated by the difference between C_{to} and C_x; (iii) The relative strength of the direct signal in relation to subsequent reflected energy, as indicated by the degree of separation between C_t and C_{to}, and how this separation compares with theory, as indicated by the separation between C_B and C_x; (iv) The relative strength of the combined direct signal and reflected energy in comparison with that predicted by Barron's revised theory, as indicated by the separation between C_t and C_B.

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