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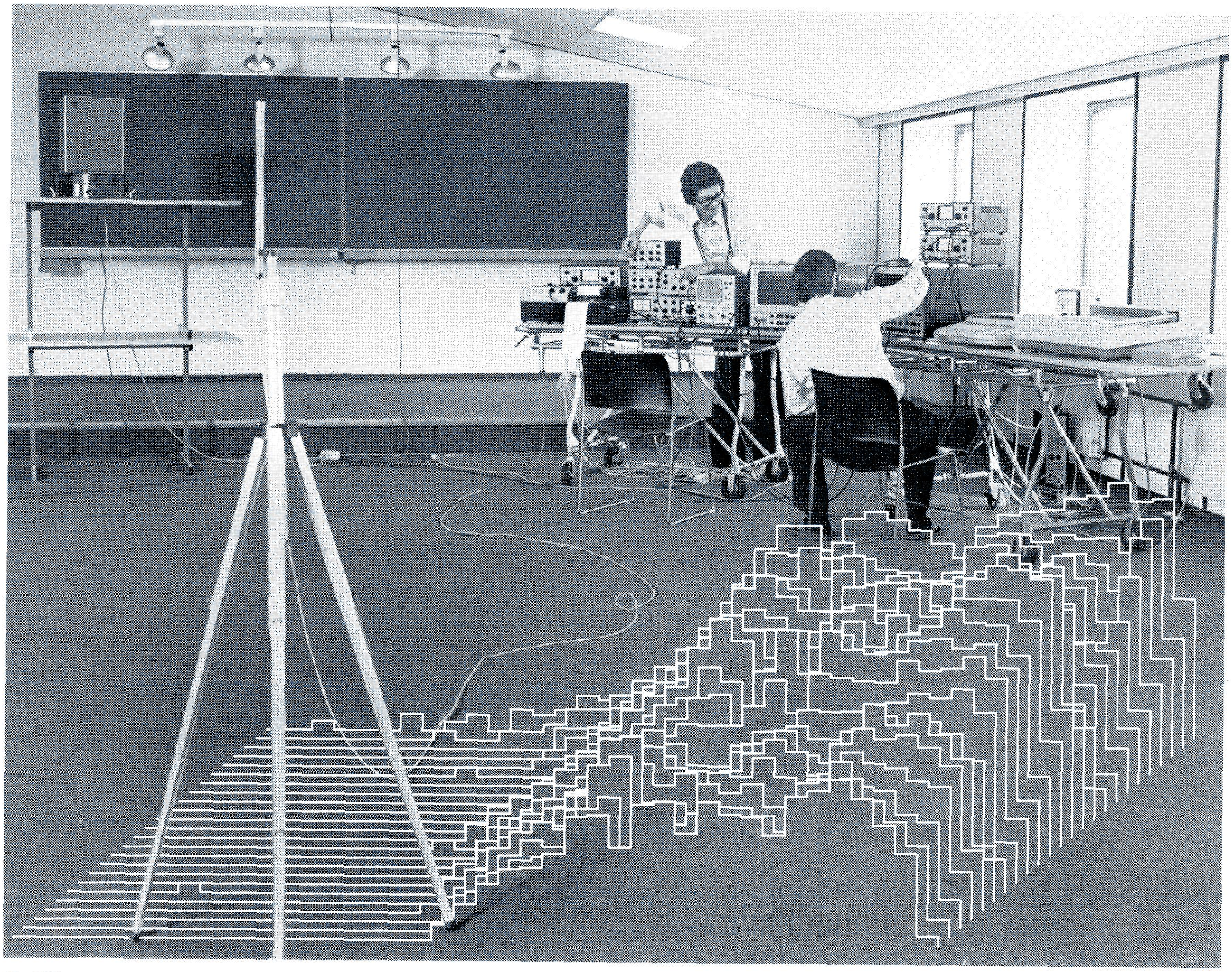
3-Dimensional acoustic measurements -using gating techniques



3-Dimensional acoustic measurements — using gating techniques

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Brüel & Kjær

1. Abstract

The subjective listening impression in a room is a function of many acoustic qualities. The more parameters that can be viewed at the same time, the easier it is to evaluate the objective qualities of the room.

This paper will therefore try to expand the traditional "1-dimensional" acoustic reverberation time measurement — first, to a "2-dimensional frequency response measurement" of the various acoustic surfaces using a gated sine tone burst, and then to a "3-dimensional" plot of how the various frequency responses change as function of time when the reflections arrive. The 3D plots are obtained using a gated pink noise pulse, a Real-Time Analyzer, a calculator and a digital plotter.

However, it requires, of course, some experience to interpret the 3D results just as it requires more experience to interpret a frequency response than a single number on a voltmeter.

The paper will show the influence of various time resolutions and frequency resolutions as well as rectangular and Gaussian time weightings.

2. Principle of Gating Techniques — using Swept Tone Bursts

One of the basic problems in room acoustic measurements has always been to determine the direction of a certain reflection, and more important, its frequency content. For example, what is the acoustic influence of a certain type of ceiling structure and surface in a concert hall or a studio.

Gating techniques are a simple solution to these problems. Gating is a selective measurement in the time domain just as frequency analysis is a selective measurement in the frequency domain. A tone burst is transmitted from a loudspeaker and measured at the listening position as indicated in Fig.1.

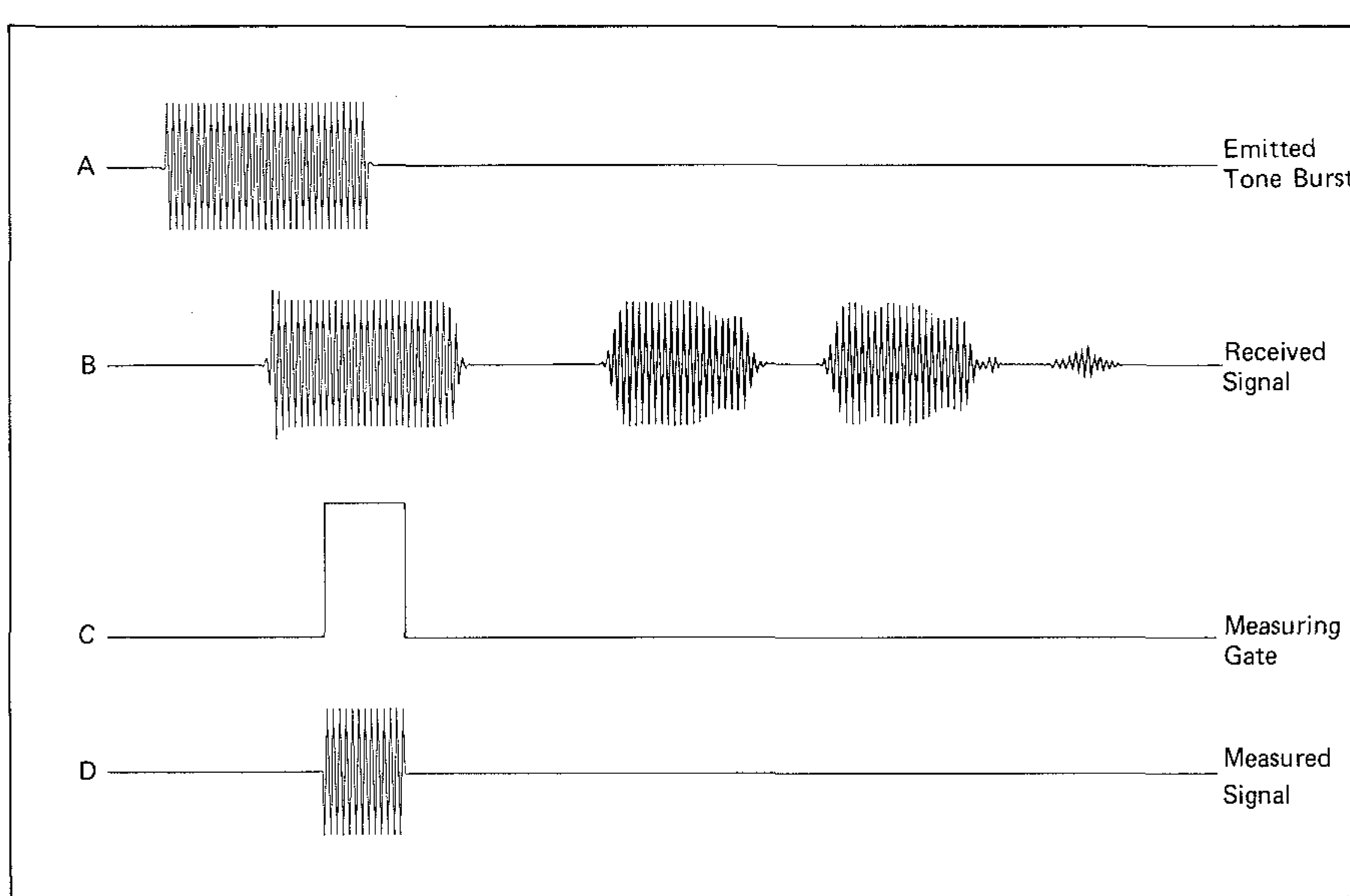

Fig.1. Principle of gated measurements

The simple implementation of this measurement is as described in the 1975 paper (Ref.1) — a swept sine that is cut into tone bursts at the zero crossings. The instrument set-up is shown in Fig.3 and the time and frequency spectra of the tone bursts are shown in Fig.4. The output of the Sine Generator 1023 is passed through the transmitting section of the Gating System 4440 and transformed into a tone burst of adjustable length (0,1 ms to 1 s) which then is fed through the power amplifier to the loudspeaker. The signal received by the microphone passes through the Measuring Amplifier to the receiving section of the Gating System where the desired portion of the signal is selected by the measuring gate, whose width and delay are also adjustable over a wide range. A peak detector measures the amplitude of the desired signal and feeds a DC voltage proportional to this value to the Level Recorder which is synchronized with the Sine Generator for automatic recording of frequency response. The peak detector contains a hold circuit which is reset for each new tone burst to permit capturing the new amplitude as the frequency changes. To monitor the adjustment of the Gating System, a two-channel oscilloscope is essential.

The restriction on lower limiting frequency is related to the size of the room, as is the case for anechoic rooms. A detailed description of this can be found in the 1975 paper (Ref.1).

The transmission of the tone burst will (as indicated in Figs.1 and 2) result in a direct received signal that obviously will arrive first, followed by a number of bursts corresponding to the reflections from the various surfaces.

In the 1975 paper (Ref.1) we emphasized the measurement of the direct sound that only contains the free-field information of the loudspeaker itself, while this paper will concentrate on the measurement of the reflections in order to obtain information about the acoustic properties of the room. The measurement set-up is essentially the same as in Fig.3 except the measuring gate is adjusted so it only picks up the information corresponding to a particular acoustic surface.

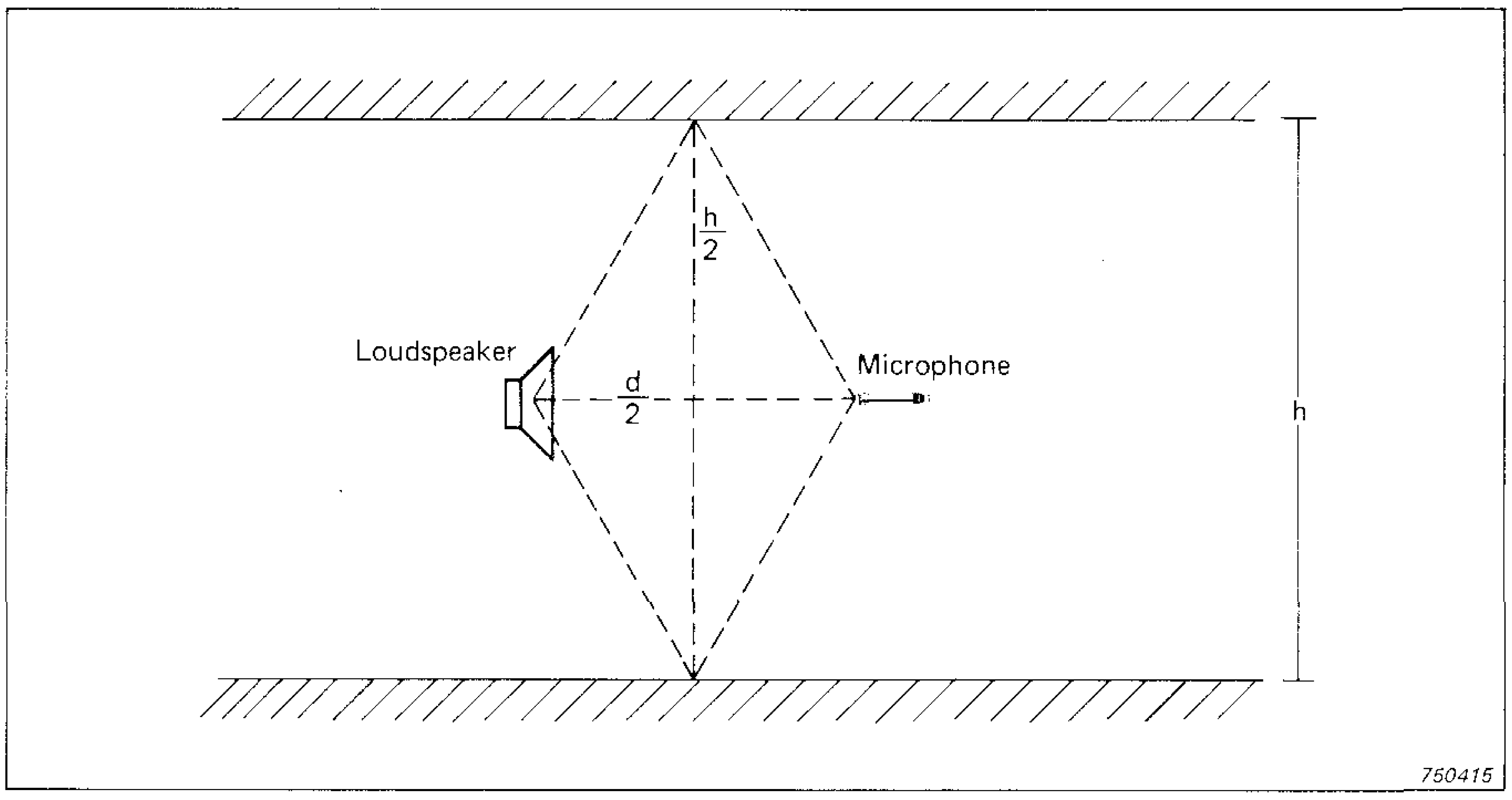

Fig.2. **Reflections from the environment**

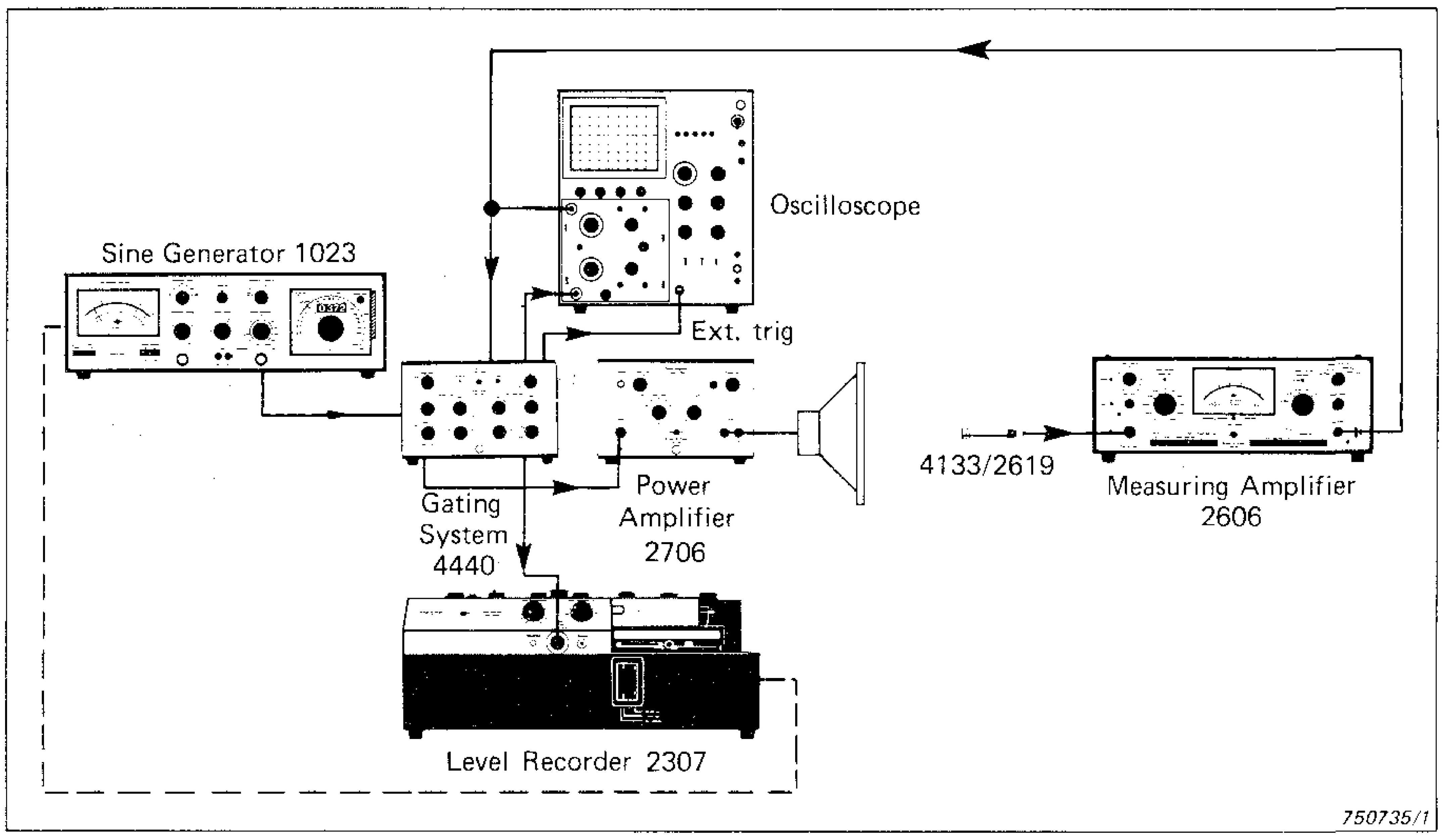

Fig.3. **Set-up using Gating System**

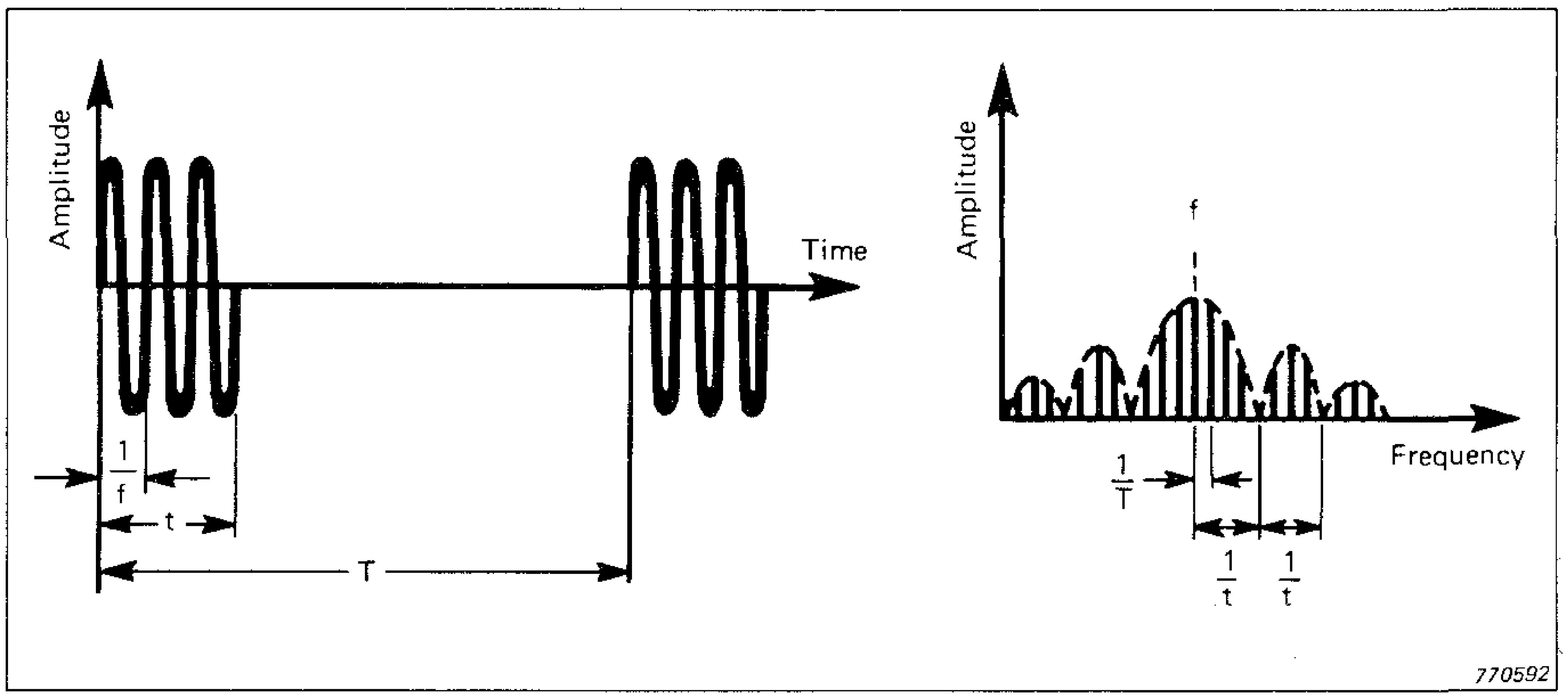

Fig.4. **Time and frequency spectra of gated sine wave. Notice that a narrow time spectrum corresponds to a broad frequency spectrum and vice versa**

3. Measurements of Frequency Response of Acoustic surfaces — using Gating Techniques with Swept Sine Bursts

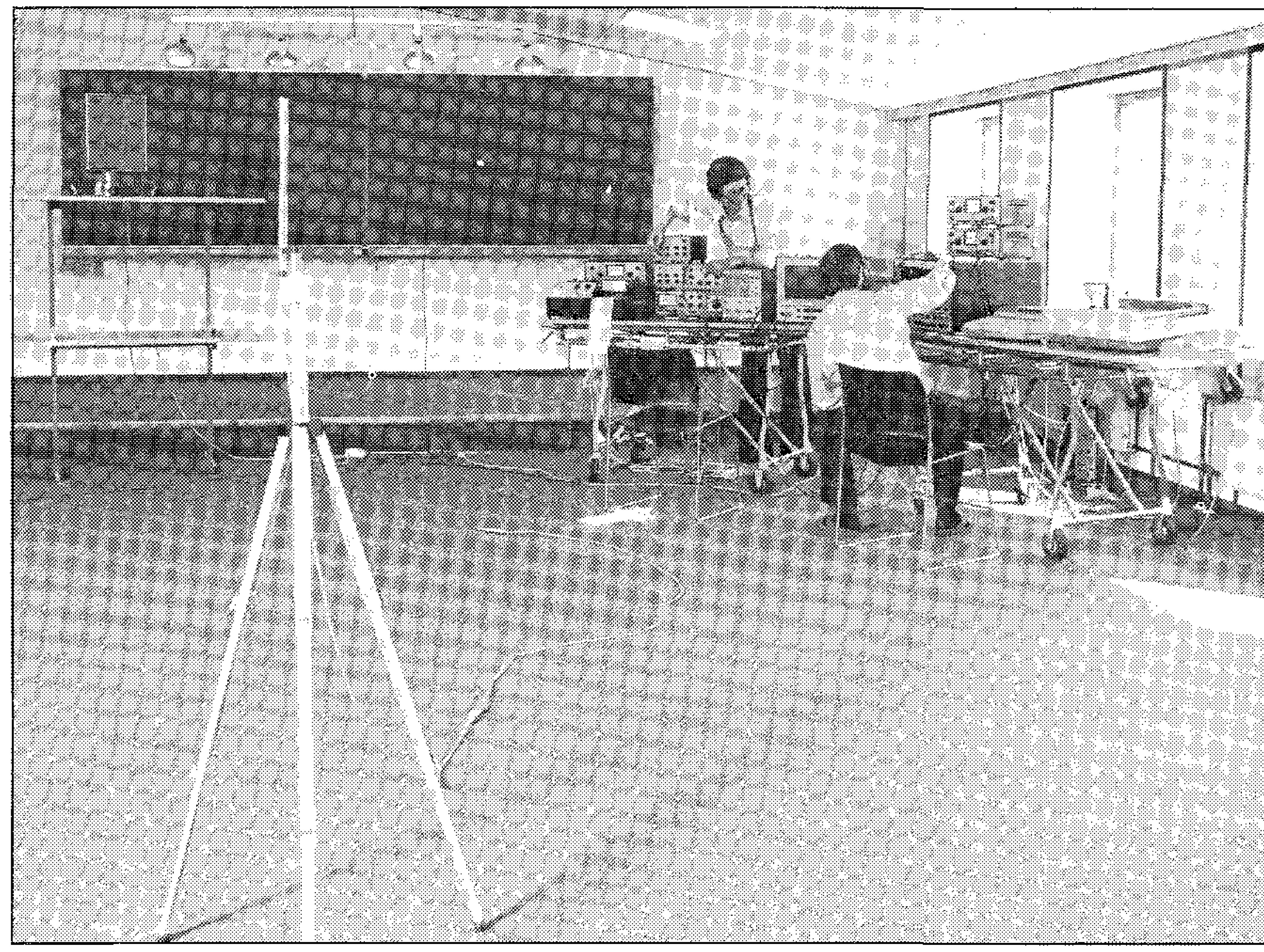

Fig.5. The lecture room under test

We selected an acoustic environment of medium size as indicated in Figs.5, 6 and 7. The dimensions were:

length 12,1 m
width 8,2 m
height sloping from 2,2 m to 3,4 m

Before measuring the acoustic surfaces of the room, we measured the "free-field" responses of the loudspeaker used. The frequency responses at a distance of 2, 4 and 6 m are shown in Fig.8 and the directional characteristics for 1, 2, 4, 8 and 16 kHz are shown in Fig.9.

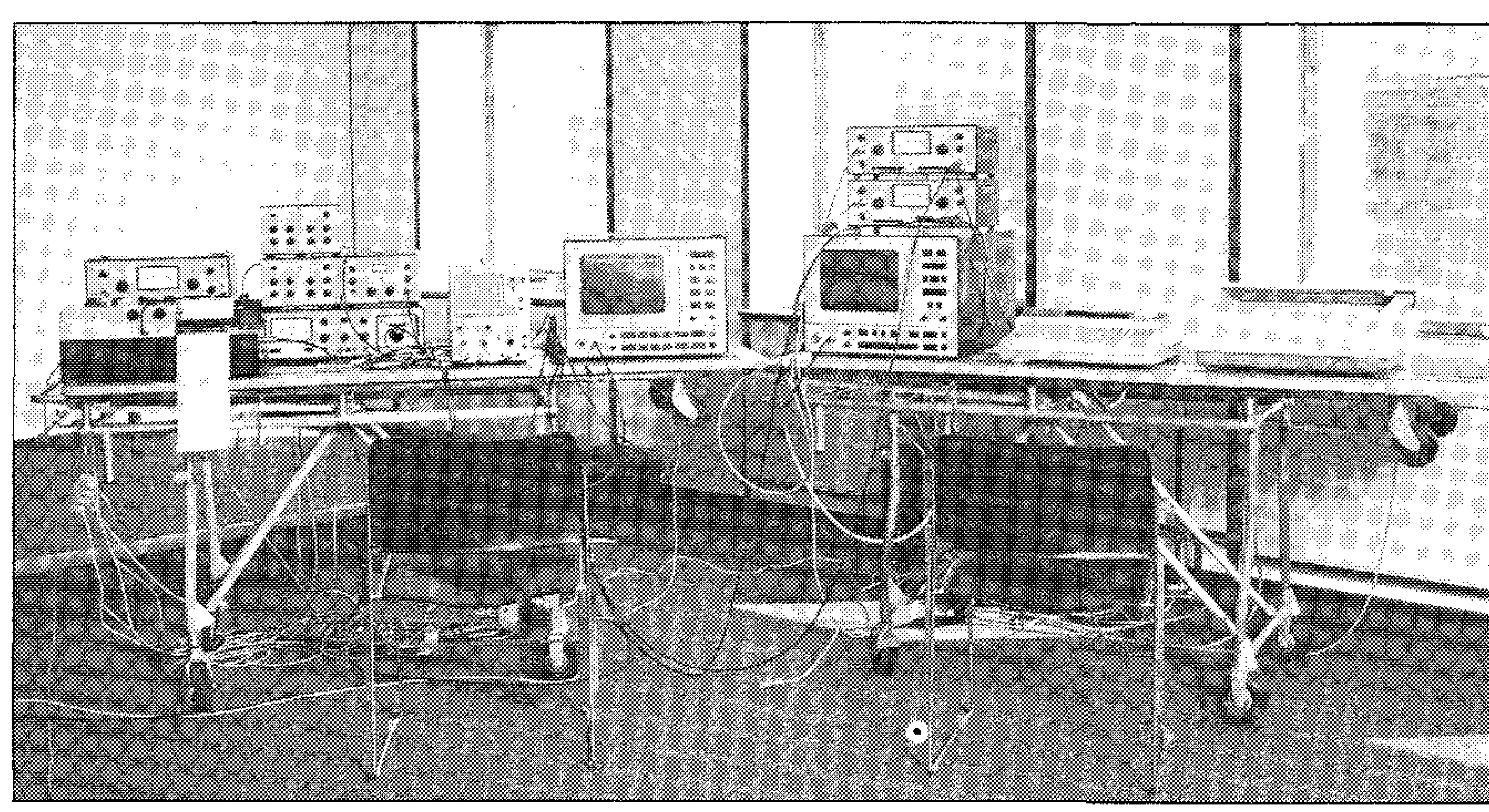

Fig.6. The instrument set-up in practice

Of course, the measurements of the surfaces must be seen relative to the frequency response as well as the directional characteristics of the loudspeaker but for some applications the directional characteristics can be neglected.

The first thing to do, in practice, is to manually sweep the frequency up and down, change the width of the transmitting gate and the repetition rate, and watch the scope until some well-defined bursts become visible. Then move the microphone around in the listening area to see how much the particular reflections change and select a typical and clearly recognizable position. Such a picture is shown in Fig.10. This was actually recorded using the Digital Event Recorder 7502 with a 4 k memory and then plotted on the Level Recorder 2307. However, normally the scope picture is sufficient.

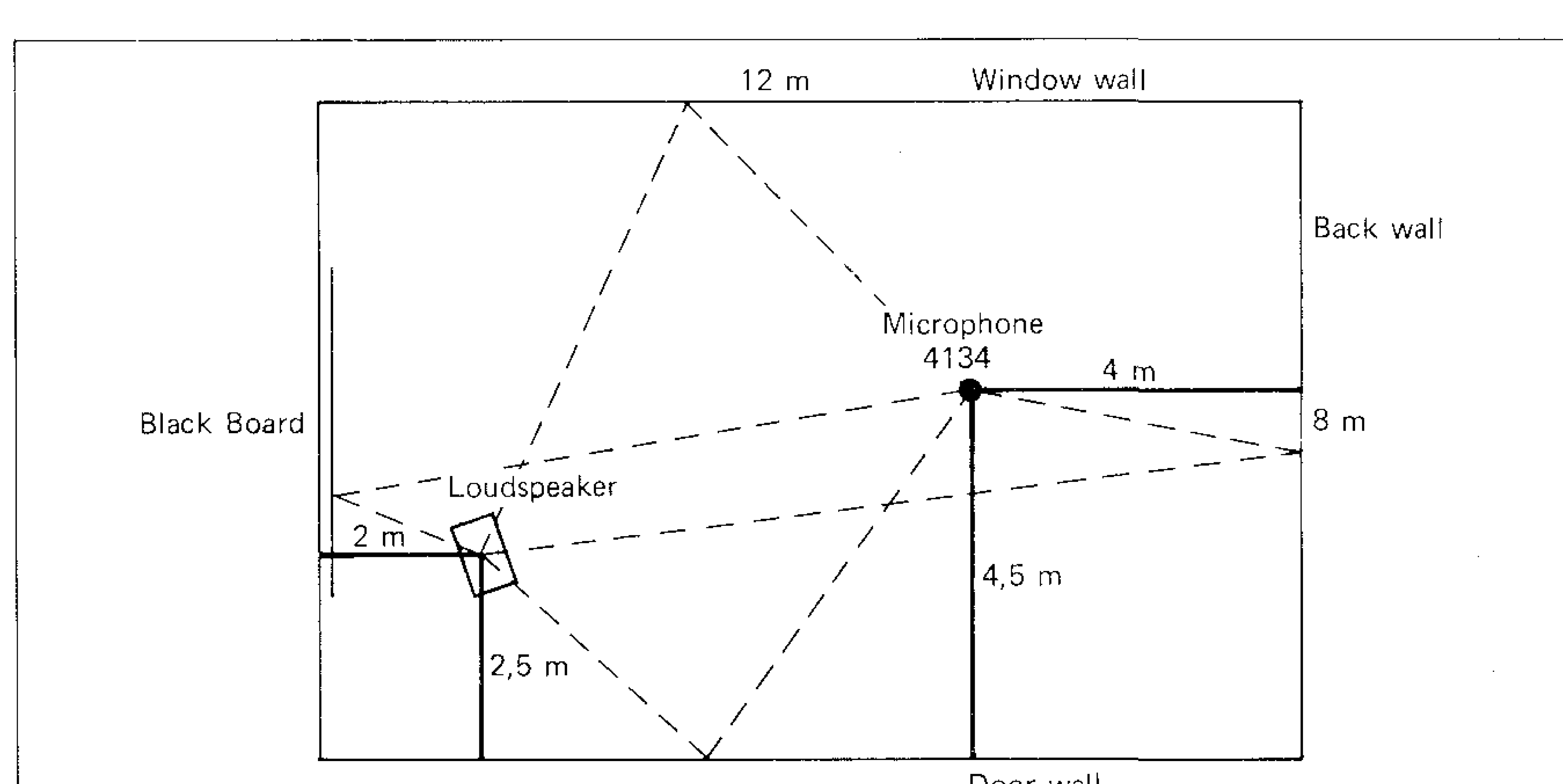

Fig.7. Schematic drawing of the lecture room

To determine which reflections correspond to the various surfaces, simple geometry can be used as indicated in Fig.7. However, in practice, it will often be easier to use an acoustic screen (this Application Note will work quite well) and manually positioning this between the microphone and the various reflecting surfaces and watching the scope until only one of the bursts disappears. When that happens the reflecting surface is determined.

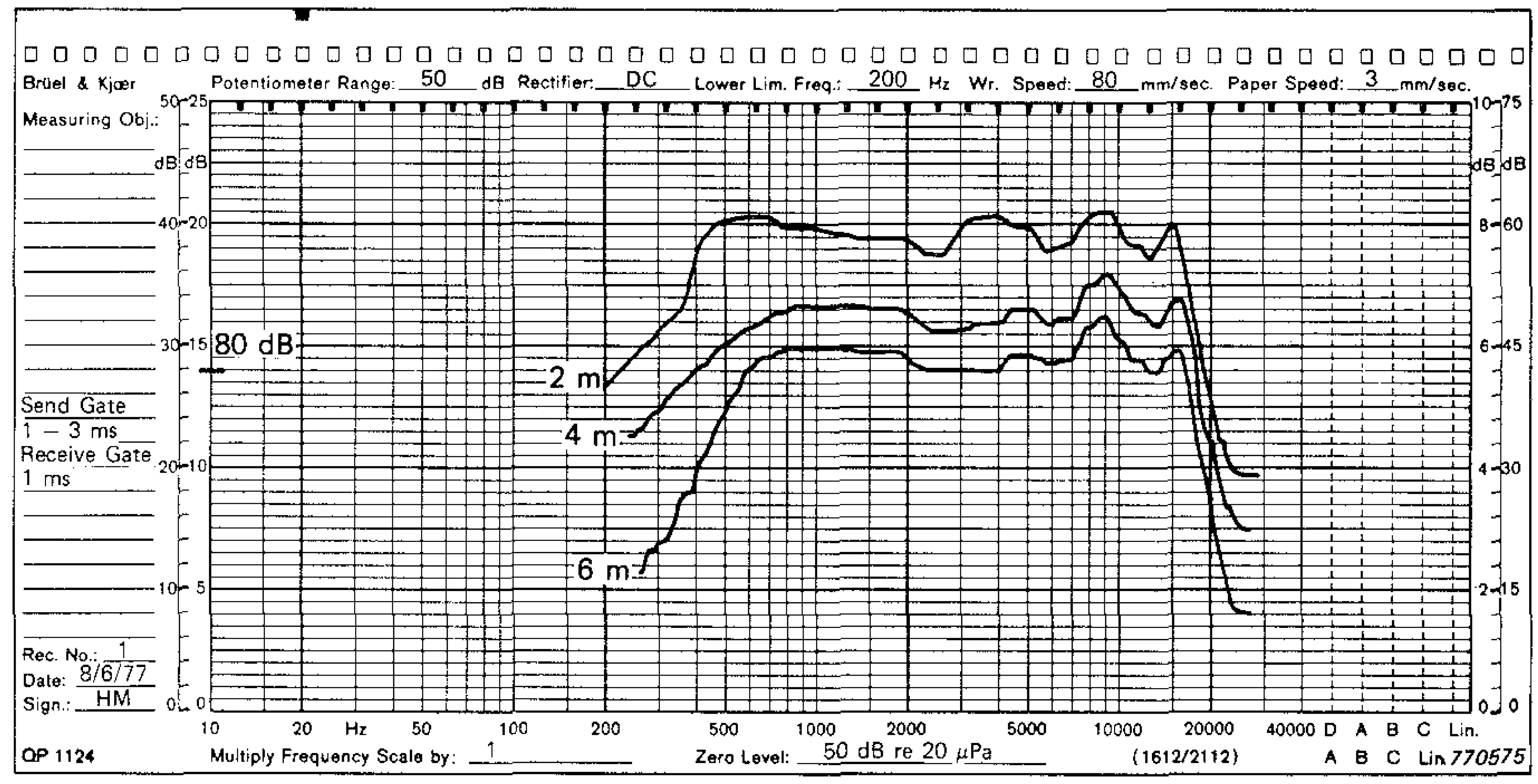

Fig.8. "Free-field" measurements of the loudspeaker used

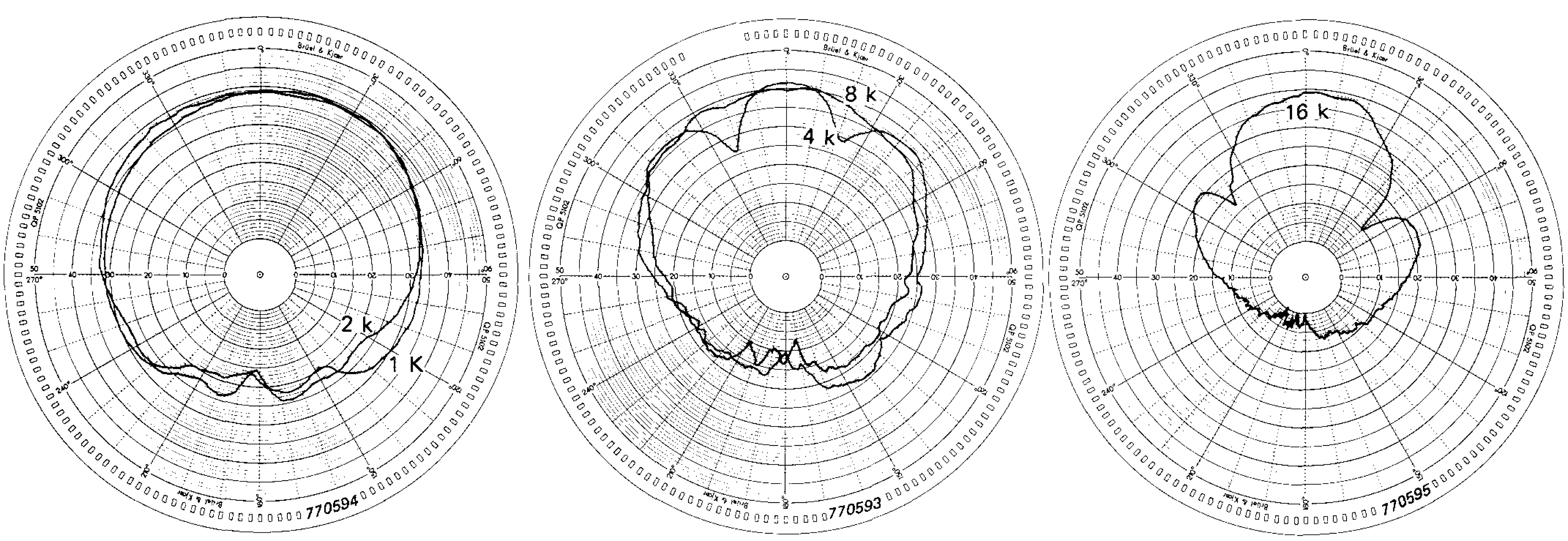

Fig.9. Directional characteristics of the loudspeaker used

The most prominent reflections for the selected loudspeaker-microphone position are indicated in Fig.10 using a 3130 Hz tone burst of 1,6 ms width. It can be seen that at this frequency the "Black Board reflection" is slightly out of phase with reflection from the wall behind it — and the direct sound and the reflections from them therefore is quite small.

However, ceiling/floor, the door wall, the window wall, and the back wall are clearly visible. The blackboard reflection can clearly be seen by changing the frequency slightly.

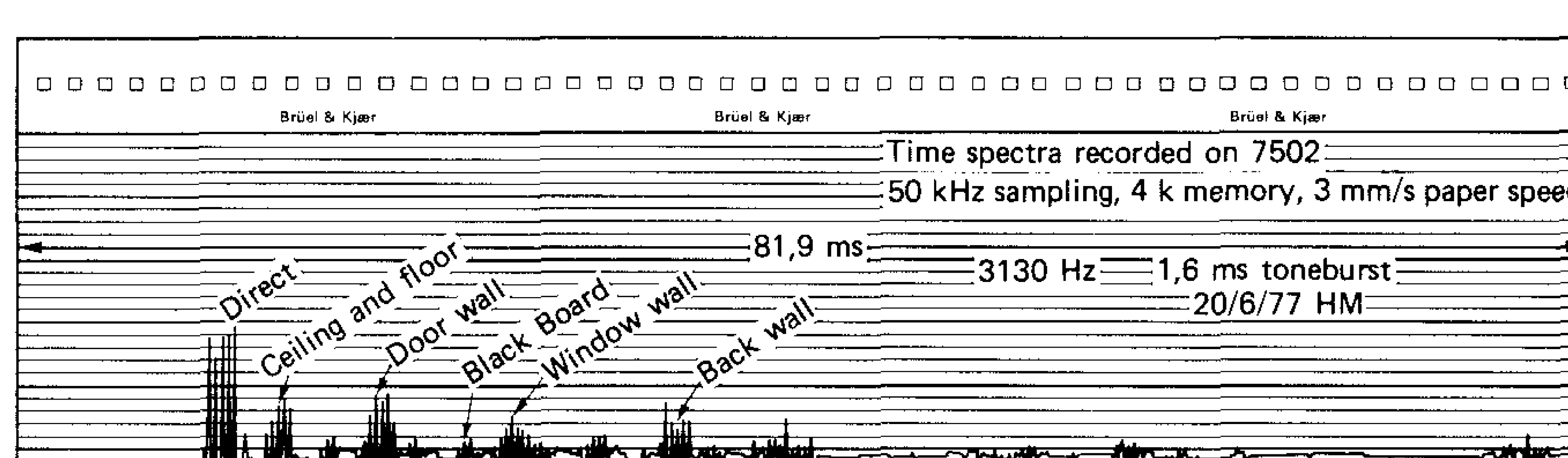

Fig.10. The time function of the various reflections in the lecture room recorded on the Digital Event Recorder 7502 and plotted on the Level Recorder 2307

The next step is to measure the "frequency responses" corresponding to the various surfaces. These responses must, of course, be seen as the difference between the direct (or free-field sound transmitted from the loudspeaker) and the reflected sound. This is done by manually adjusting the measuring gate so it only picks up the response corresponding to one of the surfaces at a time, (for instance, as indicated in Fig.10 — the door wall information), and then start the automatic sine sweep. The results of these measurements are shown relative to the frequency response in Figs.11, 12, 13 and 14.

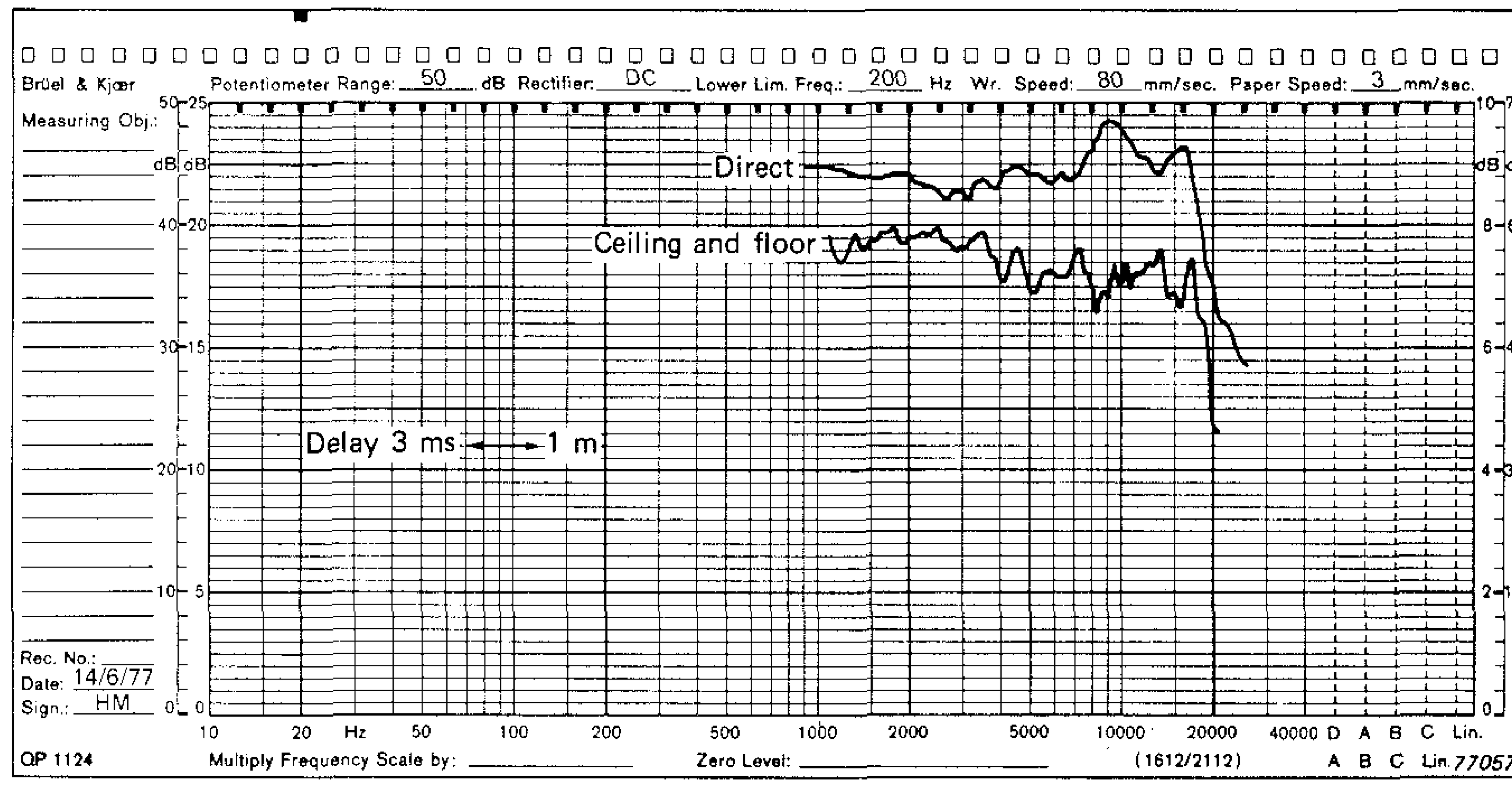

Fig.11. **The reflected sound from the ceiling and floor relative to the direct sound from the loudspeaker**

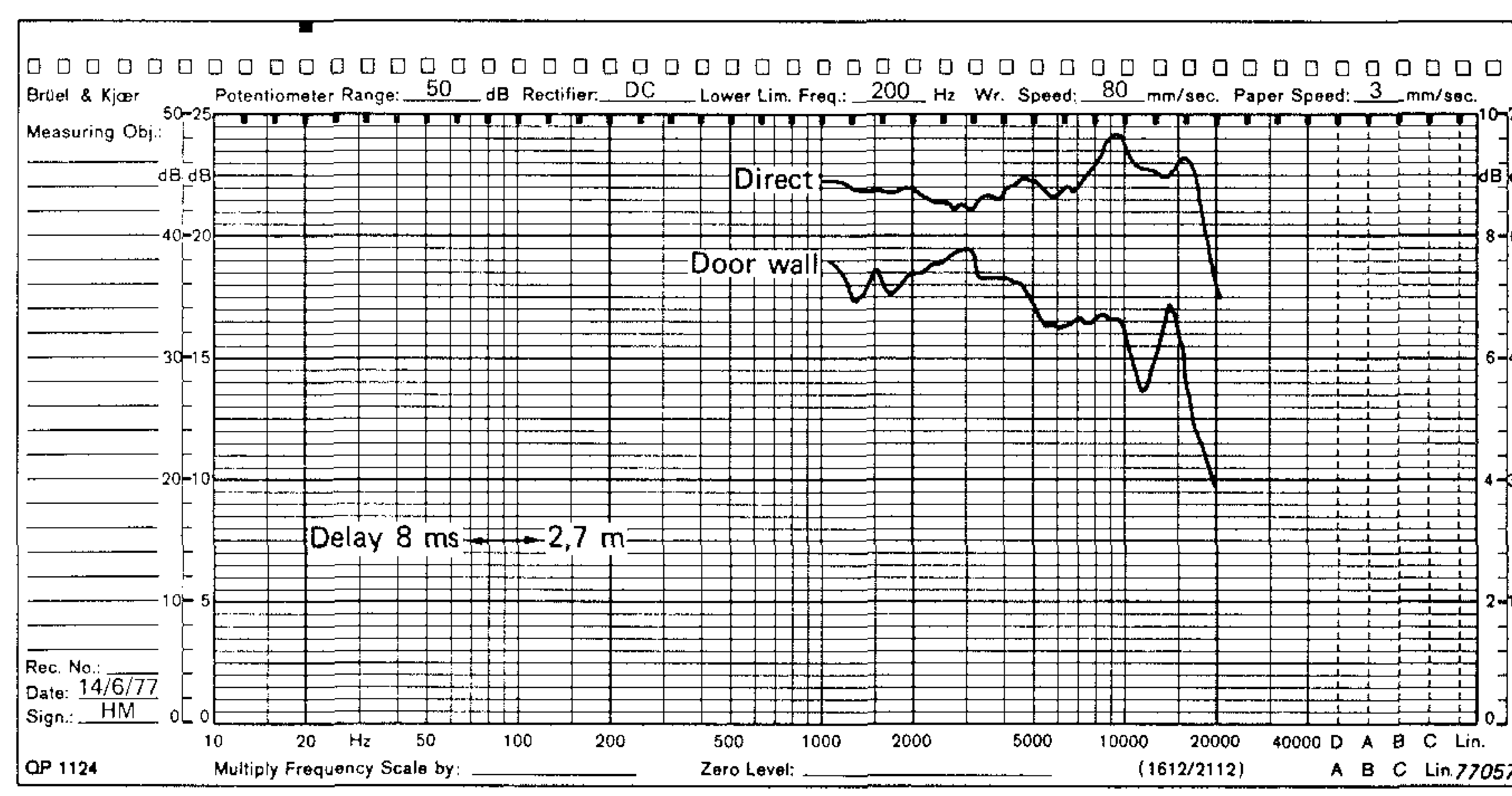

Fig.12. **The reflected sound from the door wall relative to the direct sound from the loudspeaker**

First of all, it is seen that most of the reflections on average are about 10 dB down, but they do not die down at the same rate at all frequencies. Since the four curves are different, they also indicate that the decay rates at the various frequencies are different in the different directions.

The most pronounced "problem" is probably the window wall and back wall reflections at 2—3 kHz (Figs.13 and 14) that show a significant "flutter echo" since the reflected signals are only approximately 1 dB down after 15 ms and 24 ms respectively.

Obviously, the time picture (Fig.10) doesn't reveal the frequency information and the frequency pictures (Figs.11—14) don't show the time information. The solution therefore is a 3D plot of the frequency spectra as a function of time. This is virtually impossible to do manually but is quite easy using modern programmable calculators.

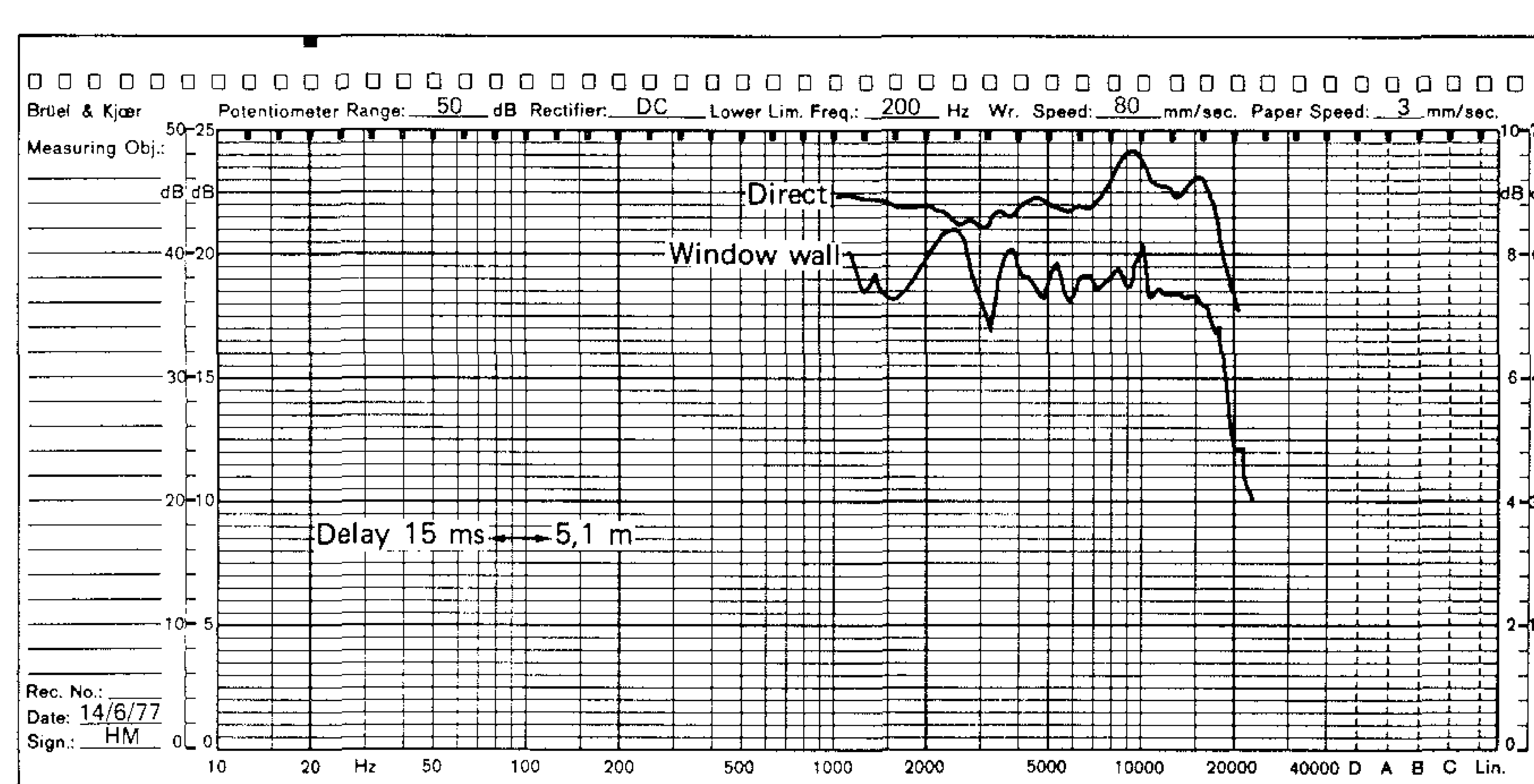

Fig.13. **The reflected sound from the window wall relative to the direct sound from the loudspeaker**

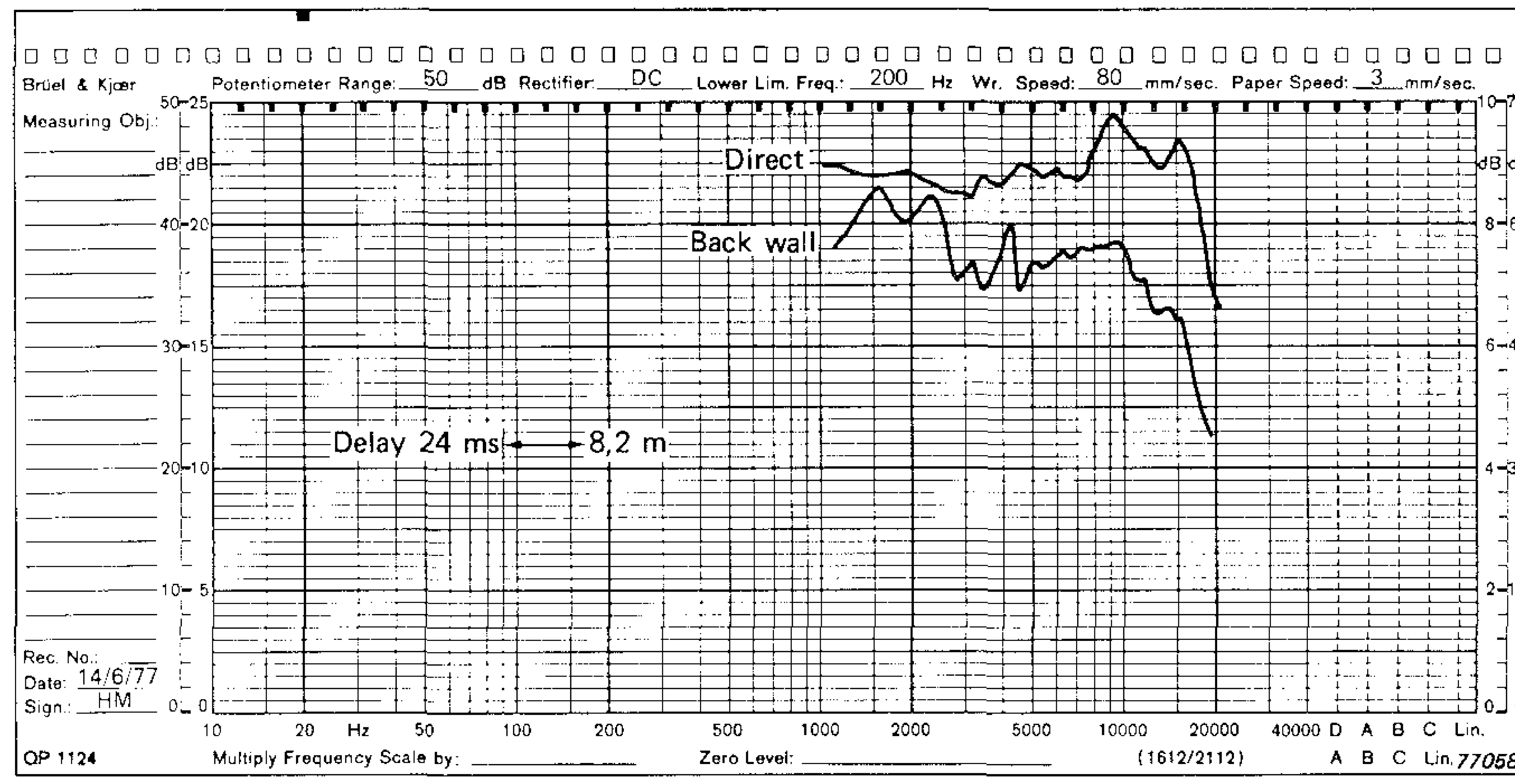

Fig.14. The reflected sound from the back wall relative to the direct sound from the loudspeaker

4. Instrument set-up for 3D Measurements

In recent years, there have been several approaches in the audio industry to introduce 3D plots, (Refs.2—6) but the expense so far has been considerable. But modern instruments and calculators connected via the IEC digital interface bus make these measurements possible at a reasonable price using the traditional "2D instruments" as the hardware basis. The instrument set-up used for this application is shown in Fig.15.

The Sine Generator 1023 is replaced by the Noise Generator 1405 since the frequency analysis is done by the Digital Frequency Analyzer 2131. The first Gating System 4440 operates as a transmitting gate that in this case cuts the pink noise into bursts at the zero crossings. The width is manually adjustable in the range 0,1 ms to 1 s. The gated pink noise pulse is introduced to the loudspeaker and picked up by the microphone. The Frequency Analyzer 2120 is just used as a high pass filter in order to avoid the low frequencies that make the scope picture unstable. It also removes the low frequency information which is measured with too much statistical uncertainty to be useful due to the narrow measuring gate. A further discussion of the relation between frequency resolution and time resolution follows in section 5.

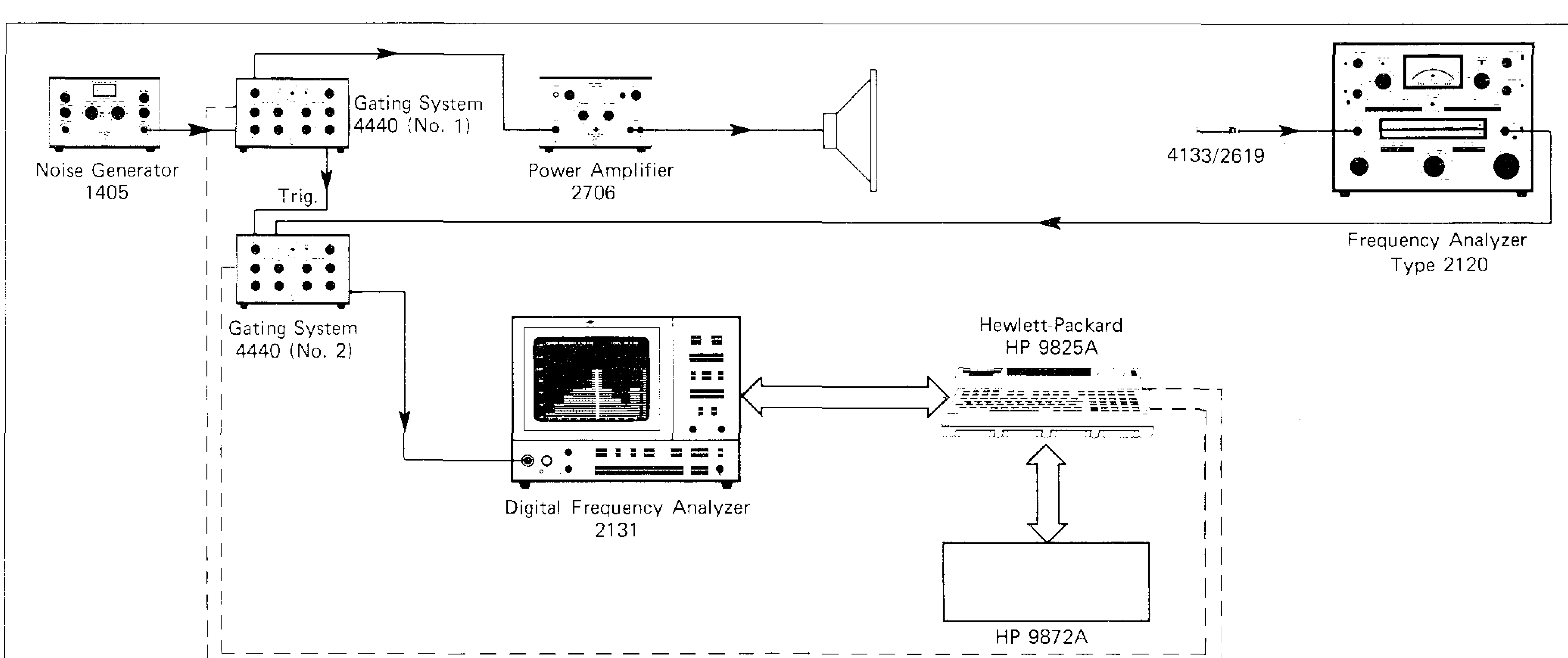

Fig.15. The instrument set-up using gated pink noise, real-time analysis and automatic control by calculators

The second Gating System is used as an analogue measuring gate (Fig.16) which is required since the normal built-in measuring gate only measures the highest positive peak that was in the signal while the measuring gate was open. In other words the gated information is only available as a DC voltage when only one Gating System 4440 is used; but it is available as an analogue voltage, that can be frequency analyzed, when two Gating Systems are used. A Gauss Multiplier is also usable as described in section 8. This set-up can, of course, be manually operated as indicated in Figs.15 and 16 using the measuring gate of the first Gating System as a trigger for the other Gating System. By manually changing the delay of the receiving gate of the first Gating System (the trigger position) and thereby the position of the analogue measuring gate (the transmission gate of the second gating system) different parts of the received signal can be analyzed, and it can be seen how the frequency spectra change with time.

However the strong feature of the system is that it can be automatically controlled using a calculator. There are many of these on the market but B & K recommend either the HP 9825A and the Digital Plotter HP 9872A or the Tektronix 4051. These both use the IEC interface bus that most new B & K instruments are equipped with. (Note: a buffer amplifier is necessary to drive the Gating Systems from the IEC bus; or the Gating Systems can be modified for a higher input impedance.)

Depending on the software used, we can now automatically control the start of the transmission burst (Gating System No.1) and the start of the receiving gate (Gating System No. 2). The widths of the transmission gate and the receiving gate are manually adjustable on the two gating systems.

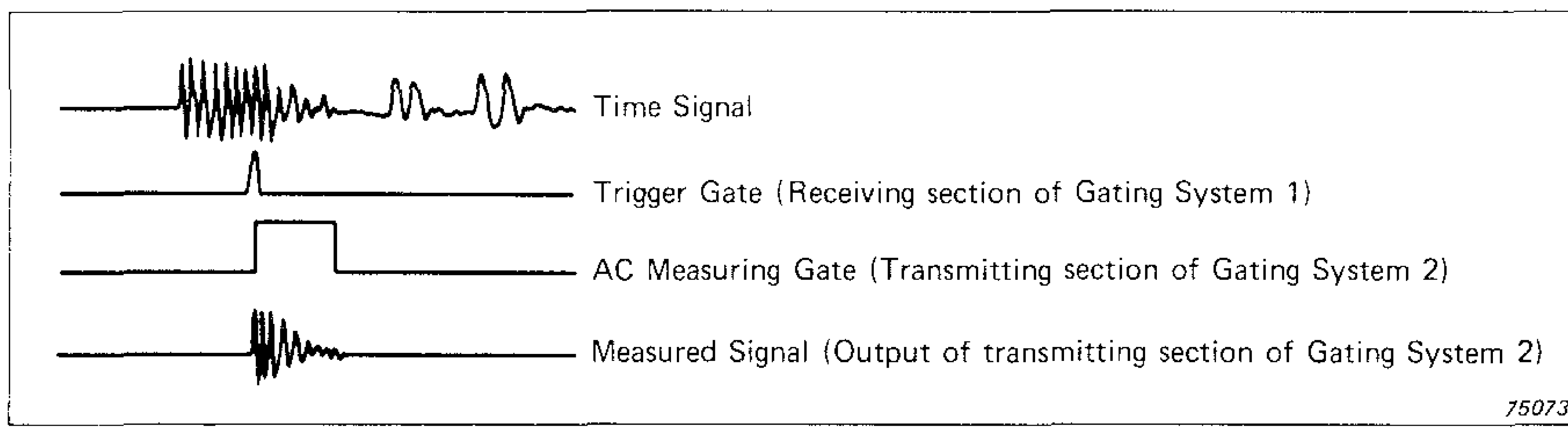

Fig.16. Setting of gates to measure the various reflections with the set-up in Fig.15

5. 3D plots of how the Frequency Spectra change with time

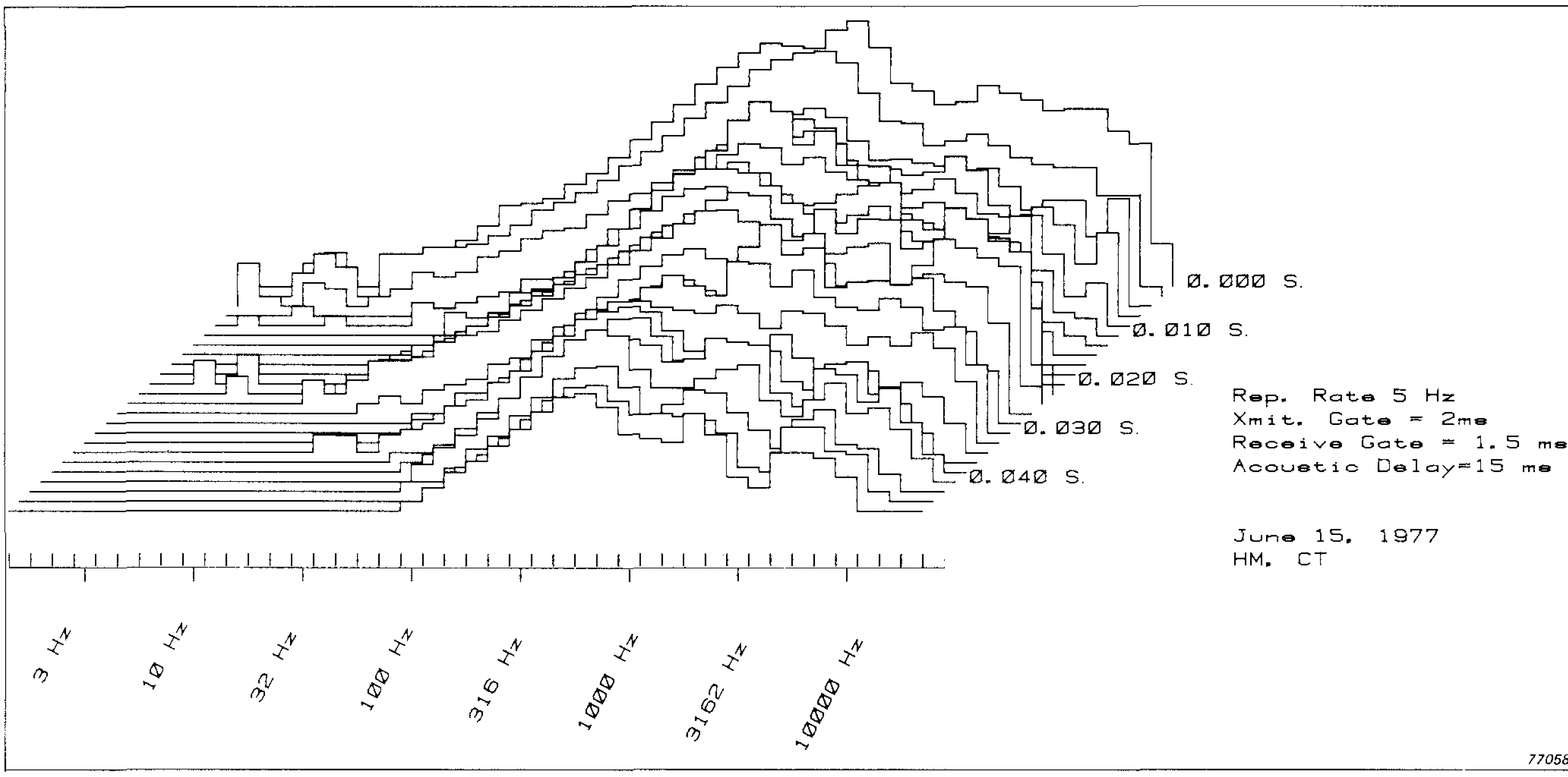

Fig.17. 3 D plot of lecture room showing how the frequency spectra change with time. 0—50 ms time axis. Receiving gate 1,5 ms

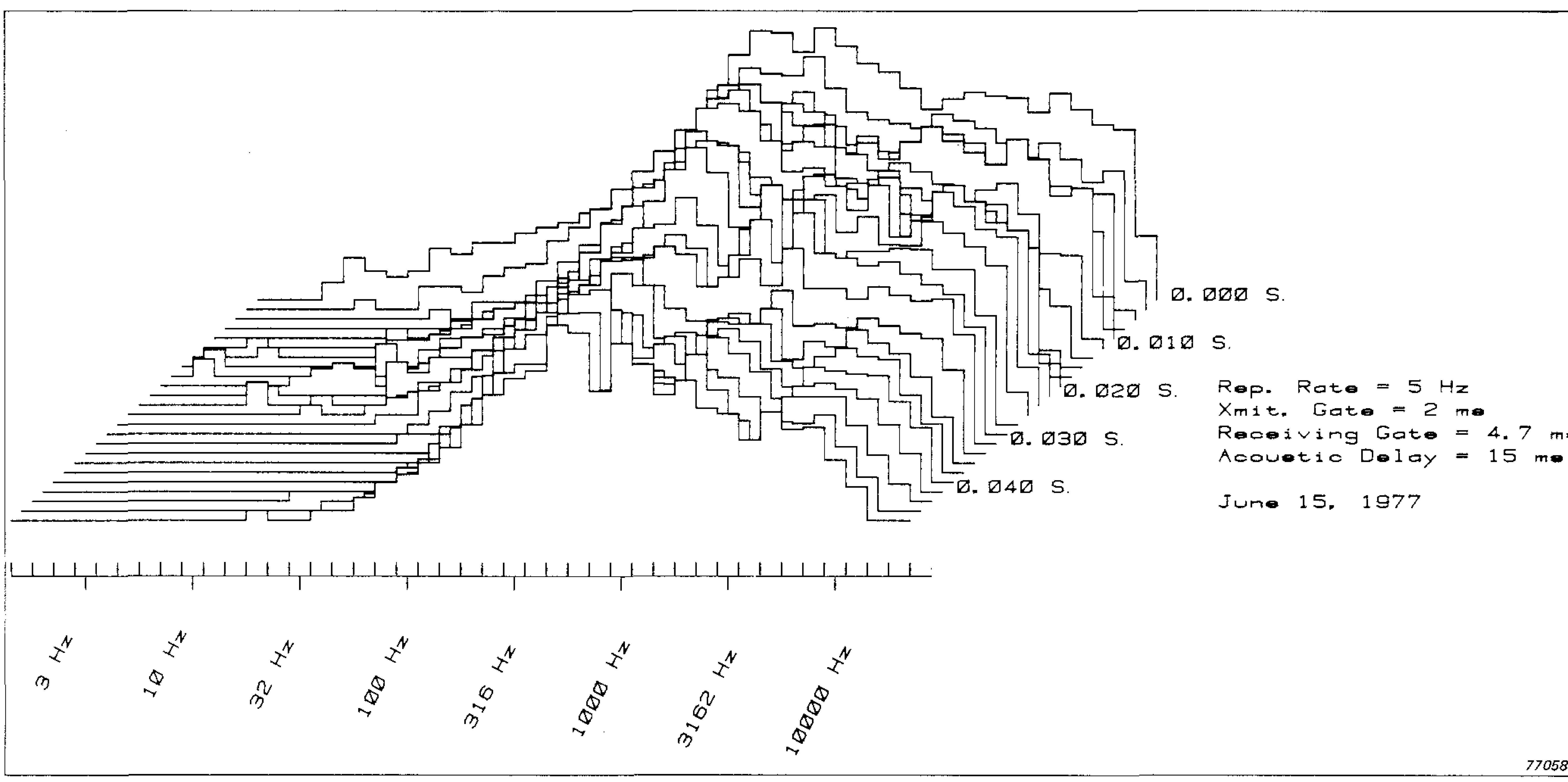

Fig.18. 3 D plot of lecture room showing how the frequency spectra change with time. 0—50 ms time axis. Receiving gate 4,7 ms

Typical results of this measurement are shown in Figs.17—22.

The first three plots, Figs.17, 18 and 19 are building acoustics measurements using the loudspeaker-microphone position indicated in Fig.5 and Fig.7. The three plots are essentially the same but with different time resolutions in the receiving gate: 1,5, 4,7 and 15 ms respectively, and they show how the frequency spectra change with time over the 0 to 50 ms time span.

It is seen that the very narrow measuring gate (1,5 ms) used in Fig.17 displays a visible wave structure in the 3D spectrum travelling along the time axis, while the measuring gate (15 ms —Fig.19) shows a wave structure travelling along the frequency axis. Stated another way, a short gate gives good time resolution while a long gate gives good frequency resolution.

The "flutter echo" we noticed using the simple gated sine wave (Figs.13 and 14) is clearly visible in Fig.19 but not very obvious in Fig.17 and Fig.18.

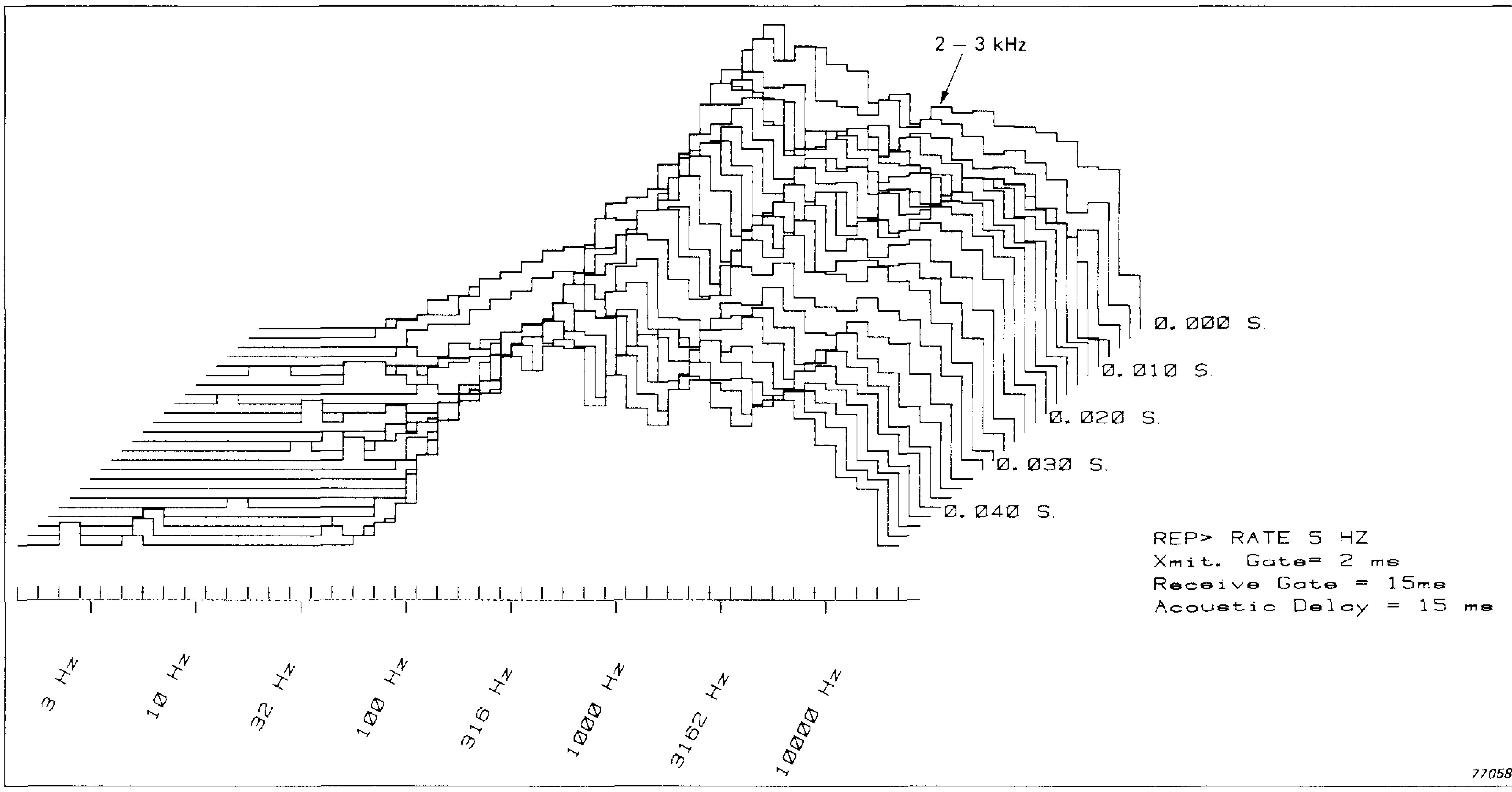

Fig.19. **3 D plot of lecture room showing how the frequency spectra change with time. 0—50 ms time axis. Receiving gate 15 ms Notice the "Flutter Echo" at 2 kHz**

As previously seen in Figs.17 to 22, the appearance of the 3 D spectrum depends on the width of the receiving gate. One may then ask, what gate width should be used to give the correct result. The answer is: "That depends on what information you want." If good time resolution is desired, a very narrow time window must be used — but this has the unavoidable by-product of giving very poor frequency resolution. On the other hand, if good frequency resolution is desired, the time resolution will be reduced. The mathematical relationship is very simple:

$$F = \frac{1}{T}$$

For example, if the receiving gate is 5 ms (= T), then the frequency resolution is 200 Hz. However, even though the receiving gate is 5 ms long, we can move it in much smaller increments — and what we see is how a given frequency component changes as a function of time — with a "spreading out" of the signal over a 5 ms interval. Richard C. Heyser has called this a "time smear" (Ref.7—9). These restrictions on time and frequency resolution should be kept firmly in mind whenever making this kind of measurement. They are equally applicable for digital and analog filters, FFT (Ref.13), and any other method. The "smear" in this type of measurement is a result of a law of nature that you can't cheat.

Since pink noise, which is a random signal, was used for these measurements, a certain amount of averaging is necessary to get reproducible results. For these measurements, averaging was performed over 15 noise bursts using a 4 s averaging time in the Digital Frequency Analyzer 2131.

6. Early reflections of the Loudspeaker used

The 3D technique is also applicable to the so-called "Early reflections" that describe how the frequency response changes with time for the loudspeaker itself. In other words, the first few milliseconds of the curves previously displayed in Figs.17—19. In this case (Figs.20-22) from 0—8 ms.

Early reflections are due to overhang of the speaker, and reflections, standing waves, and resonances in the speaker itself and especially in the cabinet. It indicates how fast the response of the system is and how much sound of its own the loudspeaker box adds to the signal.

Here again it's a question of the

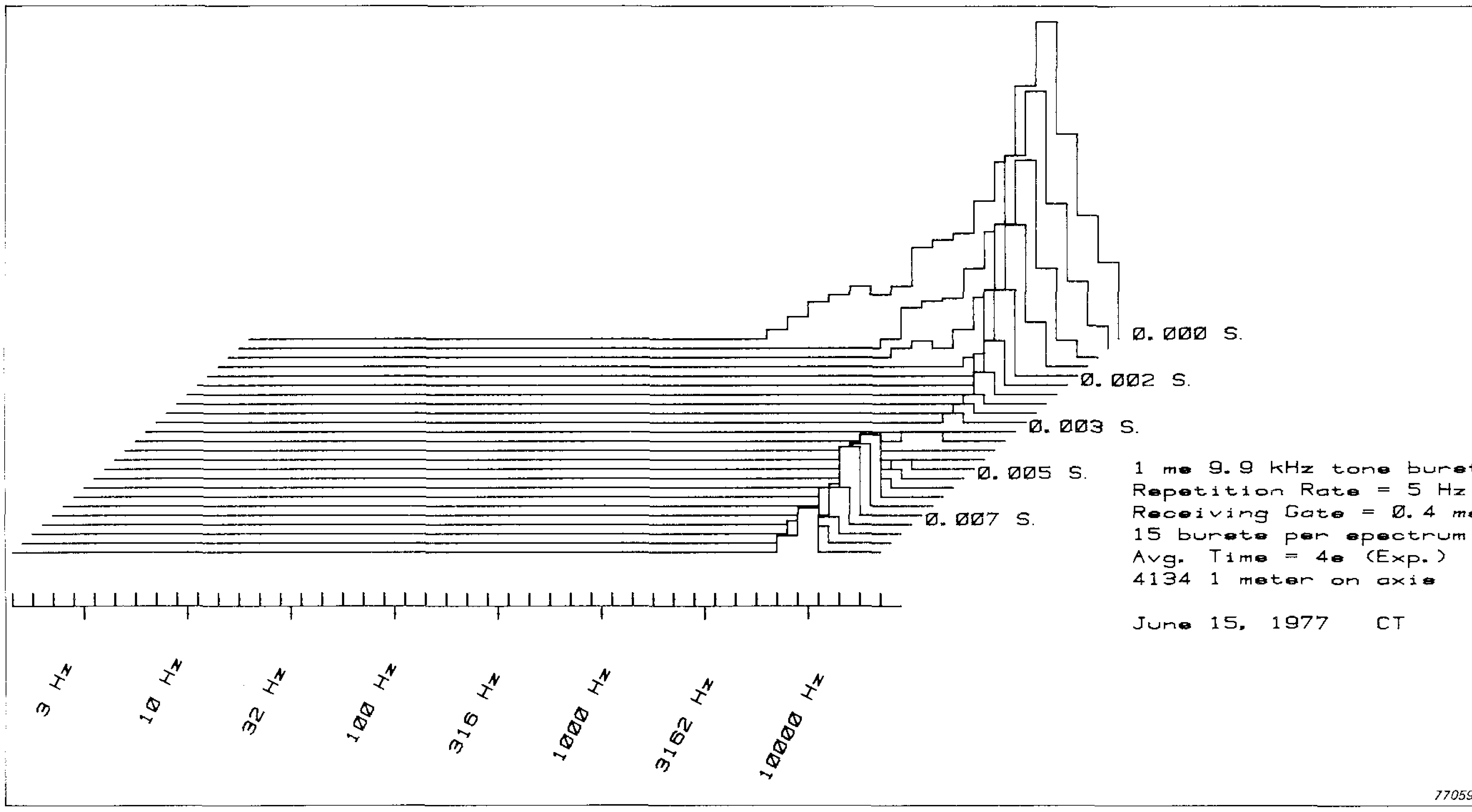

Fig.20. 3 D plot of Early Reflection of loudspeaker. Time 0—8 ms. 1 ms 9,9 kHz tone burst

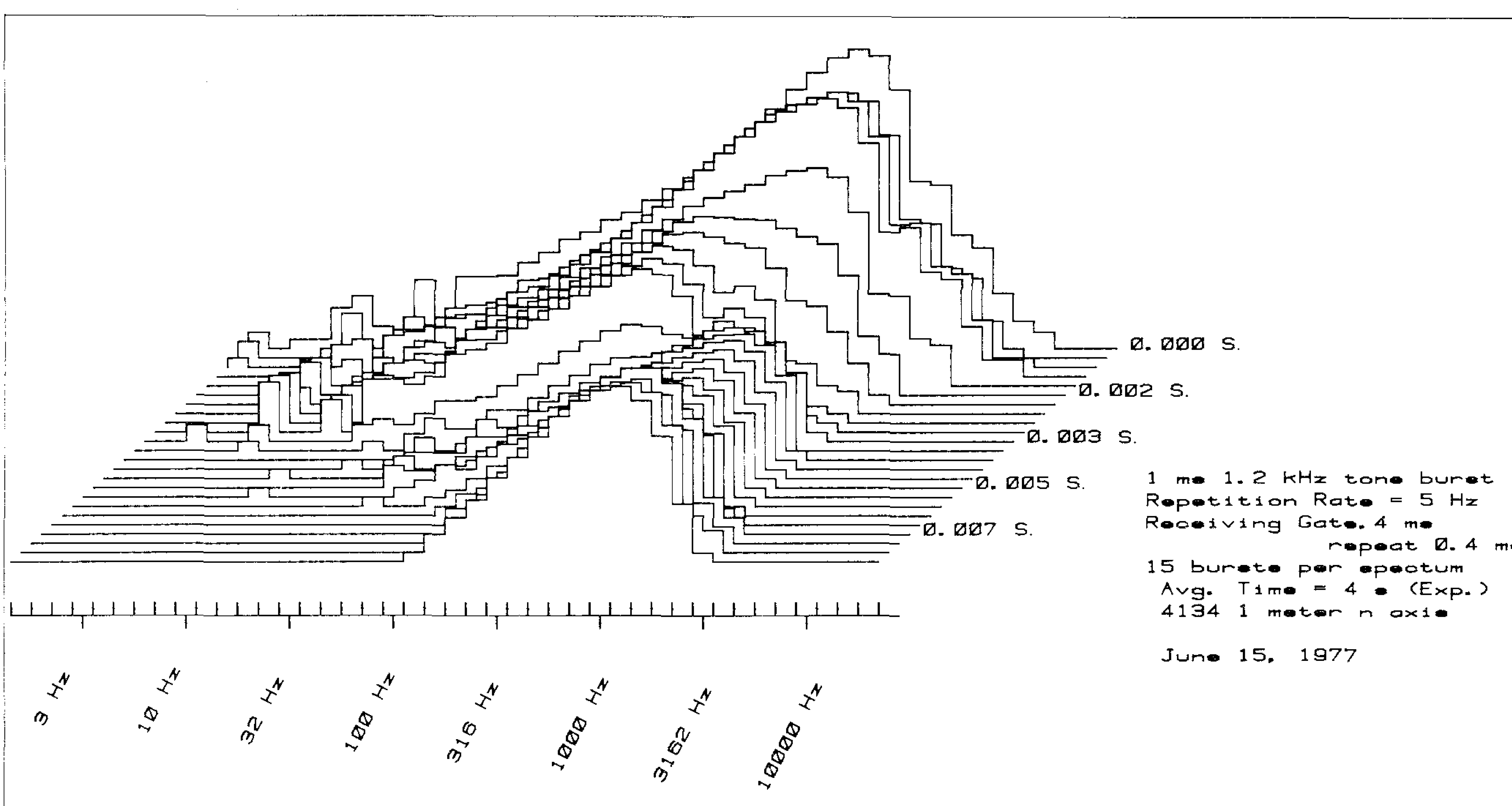

Fig.21. 3 D plot of Early Reflections of loudspeaker. Time 0—8 ms. 1 ms 1,2 kHz tone burst

optimum trade-off between frequency and time resolution. In Fig.20 we have a 1 ms 9,9 kHz tone burst and a receiving gate of 0,4 ms. In Fig.21 we have used a 1 ms 1,2 kHz tone burst and a receiving gate of 0,4 ms and in Fig.22 we have used a 1 ms gated pink noise pulse and still a receiving gate of 0,4 ms.

Obviously when only one frequency (and its sidebands because of the gating) is used as the transmitting signal the time resolution is more clearly visible. It is simply equivalent to the scope picture, but the disadvantage is that it doesn't simultaneously show the behaviour of the other frequencies as Fig.22 where we used gated pink noise.

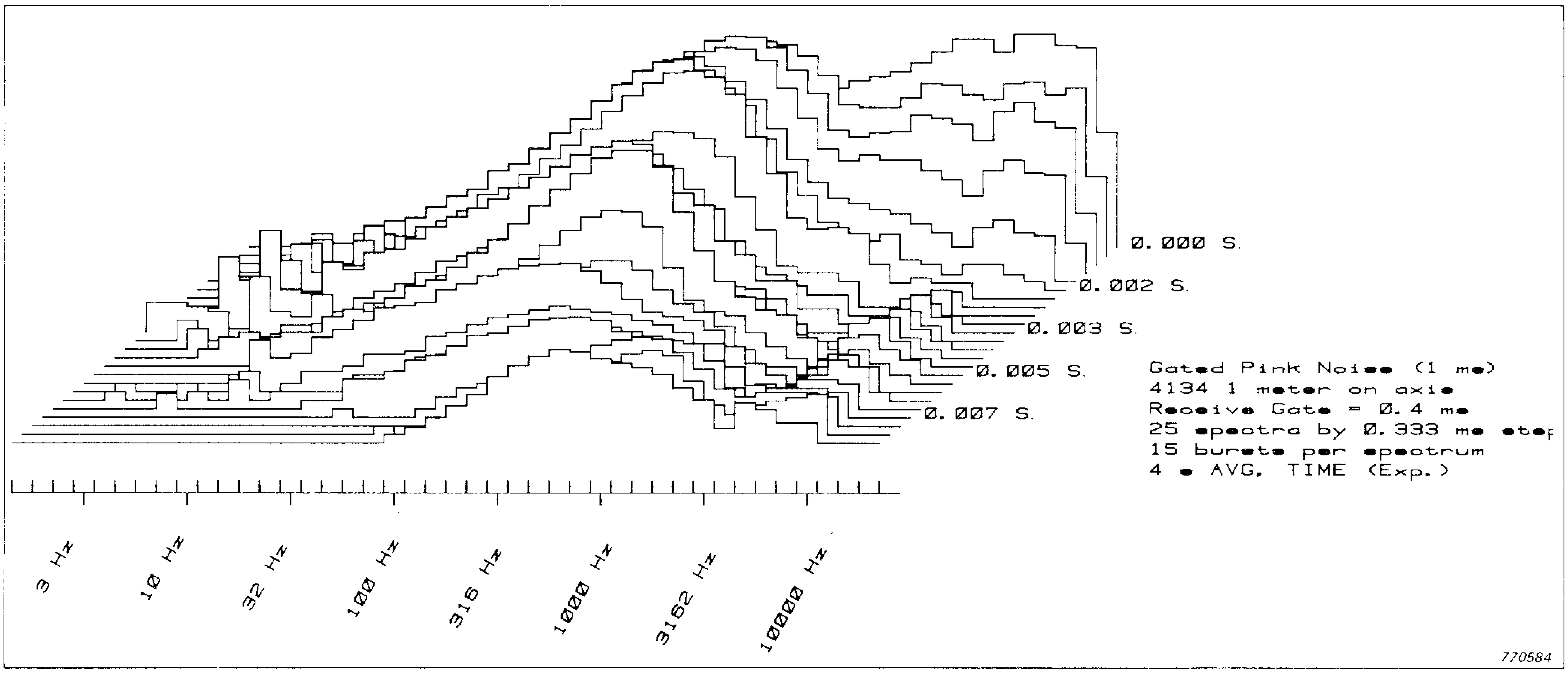

Fig.22 3 D plot of Early Reflections of loudspeaker. Time 0—8 ms. 1 ms pink noise tone burst

7. The Programs

As mentioned in section 4, the modern instrumentation has made these kinds of 3D measurements possible at a reasonable price.

Control of the instruments may be made either by the HP 9825A or the Tektronix 4051 for which B & K can offer custom-made programs. Our software specialists are working full time on this and we expect very much from this in the future. The programs used in this paper are only the beginning and really just introduce the technique.

The programs used for these plots are made for the HP 9825A and the HP 9872A. Fig.23 shows the program for control of Gating System and input of spectra and Fig.24 shows the program for 3D plot of spectra recorded by input routine.

```
0: "CONTROL OF GATING SYSTEM AND INPUT OF SPECTRA":
1: dim A$[1];trk 0;ldk 2
2: cli 7;wrt 717,"K>";wait 1000;wrt 717,"G";red 717,A$
3: wrt 717,"M?F?D=I?M>M=";wait 100
4: ent "Number of spectra? ",N
5: if N>35;dsp "Maximum number is 35!";wait 2000;gto -1
6: dim B$[302N+16];buf "in",B$,3
7: ent "SCAN LENGTH",A
8: ent "REPETITION RATE",D;1000/D→D
9: dsp "Press CONTINUE to start";stp
10: for J=1 to N
11: F+A(J-1)/N→E;D-E→B
12: for I=1 to 15
13: lcl 8;rem 8;wait E;lcl 7;rem 7;wait B
14: next I
15: wrt 717,"E?"
16: tfr 716,"in",302
17: jmp rds("in")#-1
18: wrt 717,"E=";next J
19: trk 0;rcf 1,B$;gto "end"
20: "no2131":for I=1 to 10;wait 300;dsp " ";wait 300
21: dsp "*** 2131- or interface-error ***";next I
22: "end":dsp "End of program";end
*7711


f0    : *F+1→F;dsp"Acoustic delay (ms) :",F
f1    : *F-1→F;dsp"Acoustic delay (ms) :",F

All other special function keys empty
```
770598

Fig.23. Program for control of Gating Systems and input of spectra

```
0: "3-PLOT OF SPECTRA RECORDED BY INPUT ROUTINE":
1: dim X$[6],Y$[6],B[90],C[90]
2: trk 0;fdf 1;idf C,C,C;dim A$[C-8]
3: on err "S";ldf 1,A$
4: "S":dsp "ENTER P1 AND P2 ON PLOTTER";stp
5: psc 705;scl 0,150,val(A$[1,7])-30,val(A$[1,7])+90
6: gsb "SC"
7: dsp "SELECT PEN COLOUR ! - CONT";stp
8: gsb "AX"
9: ent "TIME DIVISION BETWEEN SPECTRA ?",W
10: (C-24)/302→N
11: for I=1 to 86 by 2
12: 'U'(N-1,I)→B[I]→B[I+1]→C[I]→C[I+1];next I
13: N-1→J;gsb "PLT"
14: for J=N-2 to 1 by -1;ofs 1,1
15: for L=1 to 85;if Lmod2=1;'U'(J,L)→C[L]→C[L+1]
16: if C[L]+1<B[L+1];B[L+1]-1→C[L]
17: C[L]→B[L];next L;gsb "PLT"
18: next J;dsp "THE END";stp
19: "PLT":2.5→X;B[2]→Y;plt X,Y
20: wrt 705,"pd";for I=3 to 85
21: I-.5→X;C[I]→Y;plt X,Y
22: I+.5→X;plt X,Y
23: next I
24: 85.5→X;C[86]→Y;plt X,Y
25: 86.5→X;plt X,Y
26: val(A$[1,7])→Y;plt X,Y
27: if (J-1)mod5=0;fxd 3;wtb 705,"lb"&str((J-1)*W/1000)&" S",3
28: wrt 705,"pu";ret
29: "U":val(A$[302p1+7((p2+1)/2-1)+1,302p1+7((p2+1)/2-1)+5])→p3;ret p3
30: "SC":csiz 1,1.5;ret
31: "P":plt X,Y;ret
32: "AX":fxd 0;val(A$[1,7])-5→Y;2.5→X;plt X,Y,-2
33: for I=2.5 to 86.5 by 2
34: wrt 705,"xt";wrt 705,"pu"
35: I+2→X;plt X,Y,-2
36: next I
37: Y-.8→Y;plt X,Y,1
38: 2.5→X;plt X,Y,2
39: Y-.8→Y;9.5→X;wrt 705,"pu"
40: wrt 705,"drl.5,4"
41: for I=0 to 7;9.5+I*10→X;plt X,Y
42: wrt 705,"xt";wrt 705,"pu"
43: X-4.5→X;Y-12.5-I→Y;plt X,Y,0
44: wtb 705,"lb"&str(√10↑(I+1))&" Hz",3
45: X+4.5→X;Y+12.5+I→Y;plt X,Y,1
46: next I;wrt 705,"drl,0";ret
47: end
*19037
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770597

Fig.24. Program for 3D plots of spectra recorded by input routine

8. Gaussian or Rectangular Weighting? Pressure or Free-field Microphone?

There are several technical measuring problems involved using pulse techniques. The most obvious problem is the sidebands introduced using gating technique. This problem is described in greater detail in the 1975 paper (Ref.1).

The second consideration could be: what kind of weighting function should be used — if any. This is described in detail in Bob Randall's Application Note (Ref.10). However using the 1/3 octave resolution the influence of the weighting function is almost negligible as can be seen from Figs.25 and 26.

Fig.25 shows the difference between the rectangular weighting and the Gaussian weighting using a 5 ms burst of pink noise on the loudspeaker and it is seen that from approximately 500 Hz and up the difference is almost constant. The difference spectrum is recorded using the Digital Frequency Analyzer 2131 in the Fast comparing mode while reading out to the Level Recorder 2307. This read-out is extremely fast (paper speed 10 mm/sec).

Fig.26 shows the electrical response of the system using the Gauss Impulse Multiplier 5623. The 200 Hz roll off is due to the high pass filter in 2120.

The operation of the Gauss Impulse Multiplier 5623 is shown in Fig.27 and is described in further detail in B & K Application Note 11-194 (Ref.11). Another technical question that could be asked is what kind of microphone should be used. The directional characteristics of the 1/2" Free-field microphone 4133 show that at 20 kHz the sensitivity from the back (180°) is approximately 10 dB down and therefore we used a Pressure microphone 4134 at grazing incidence which gives the same sensitivity in all directions in the plane of the diaphragm and since we are just interested in the difference between the direct and the reflected sound this seems optimum.

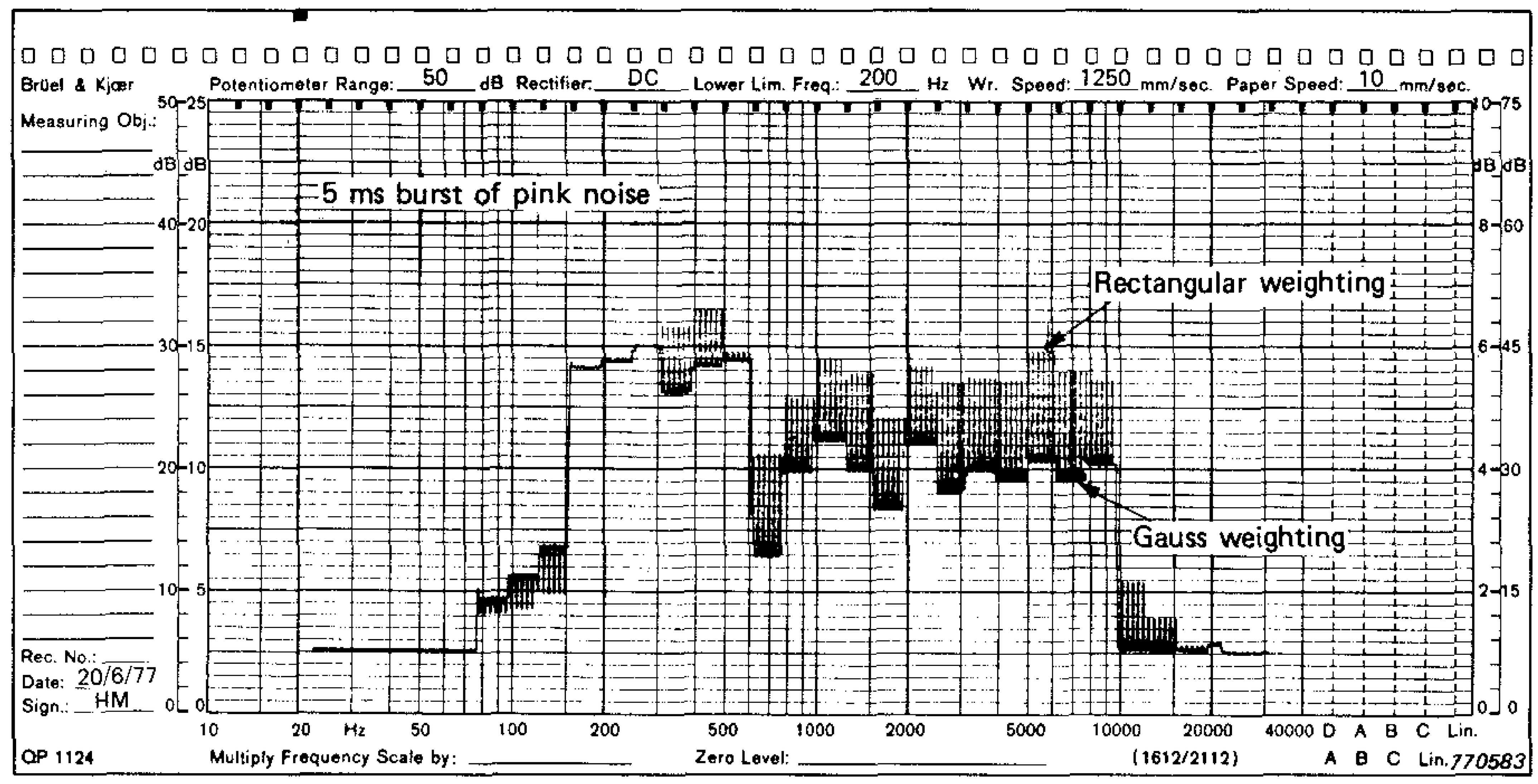

Fig.25. Difference spectrum between loudspeaker response using Rectangular and Gaussian weightings respectively. Recorded on the Digital Frequency Analyzer 2131 in the fast comparing mode

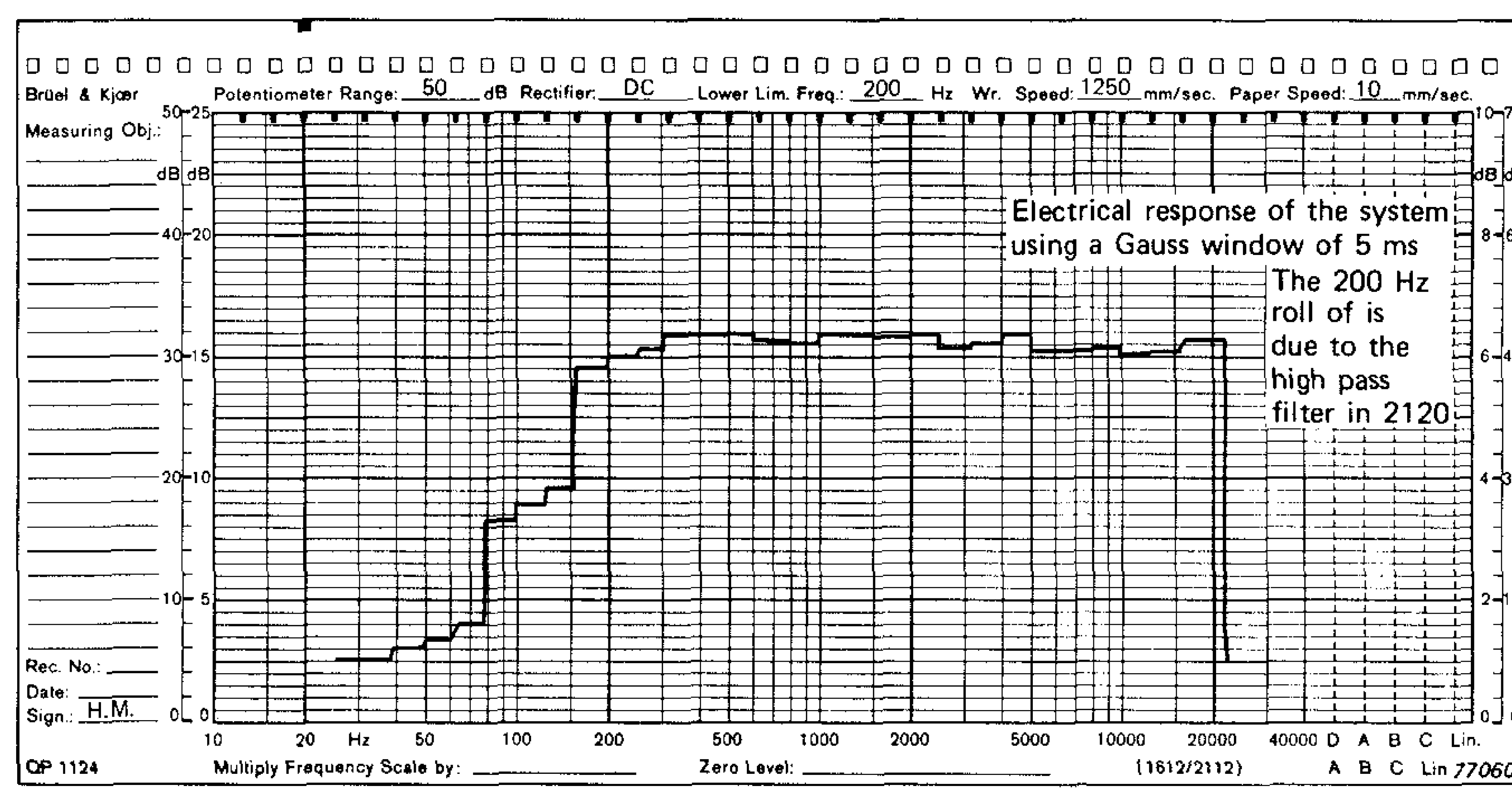

Fig.26. Electrical response of the system using Gaussian window

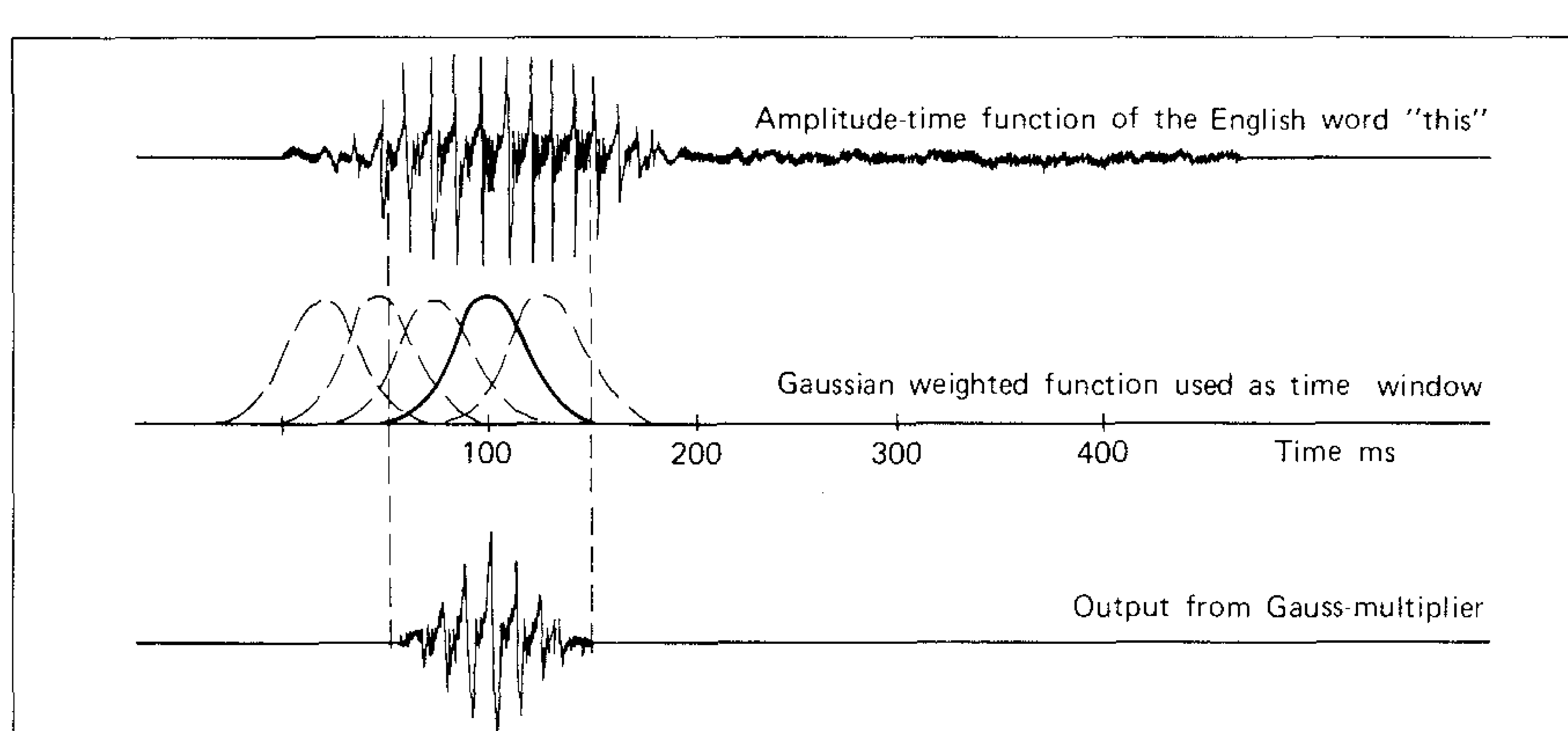

Fig.27. The operation of the Gauss Impulse Multiplier 5623

9. Transmission and Reflection of a Conventional Door

The gating technique is also very useful for measurement of transmission and reflection properties of doors, walls, etc. even as function of angle. The measuring gate is adjusted so it only picks up the reflection. As shown in Figs.28—31 we measured a conventional door as both on-axis and 30° off-axis. Fig.28 shows that the attenuation 30° off is approximately 25 dB but slightly worse at higher frequencies. Fig.29 shows that the same door "on axis" has the lowest attenuation in the critical range 3 kHz. Here it is only 18 dB.

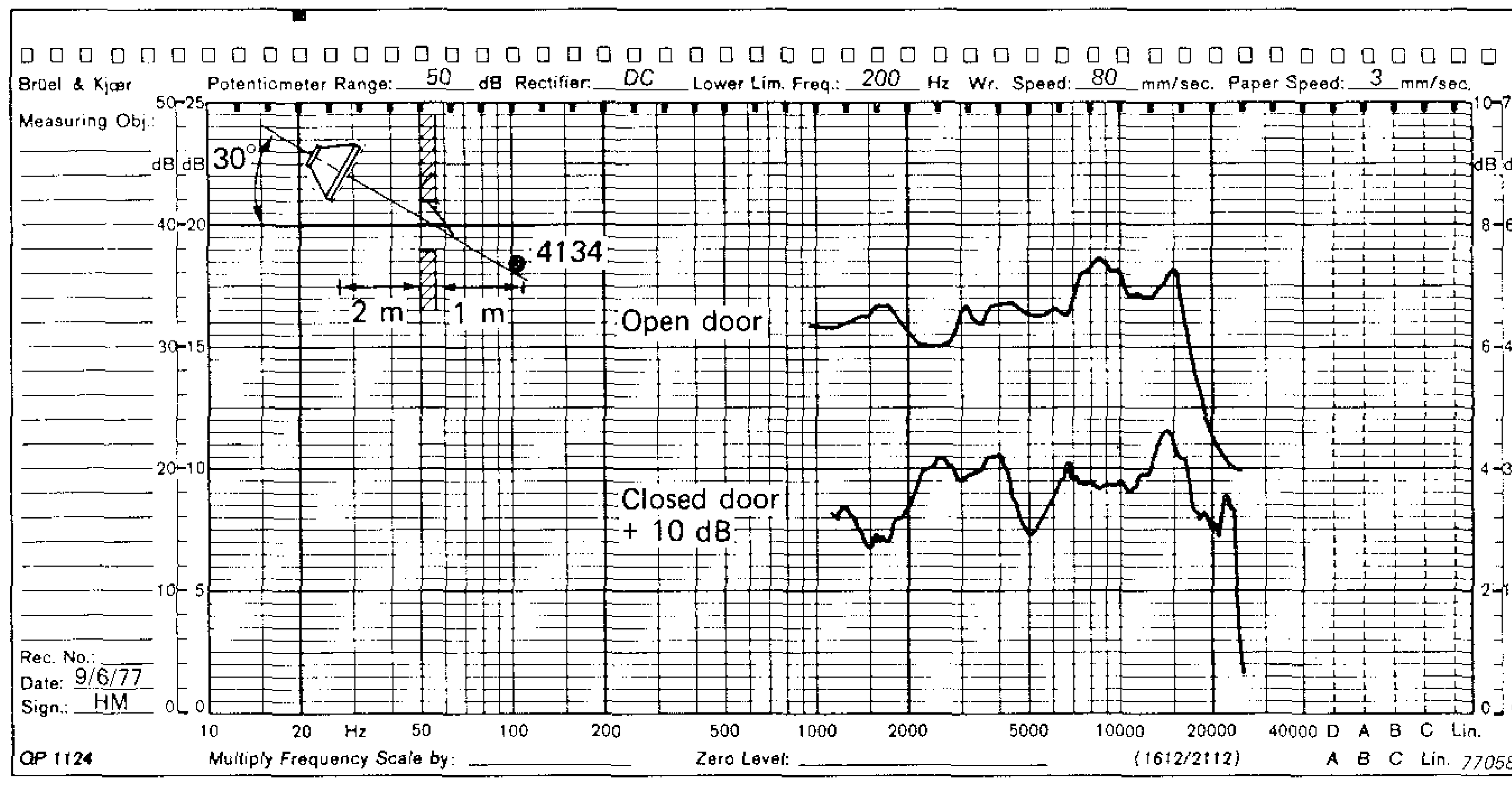

Fig.28. Spectra of conventional door open and closed. 30° off axis

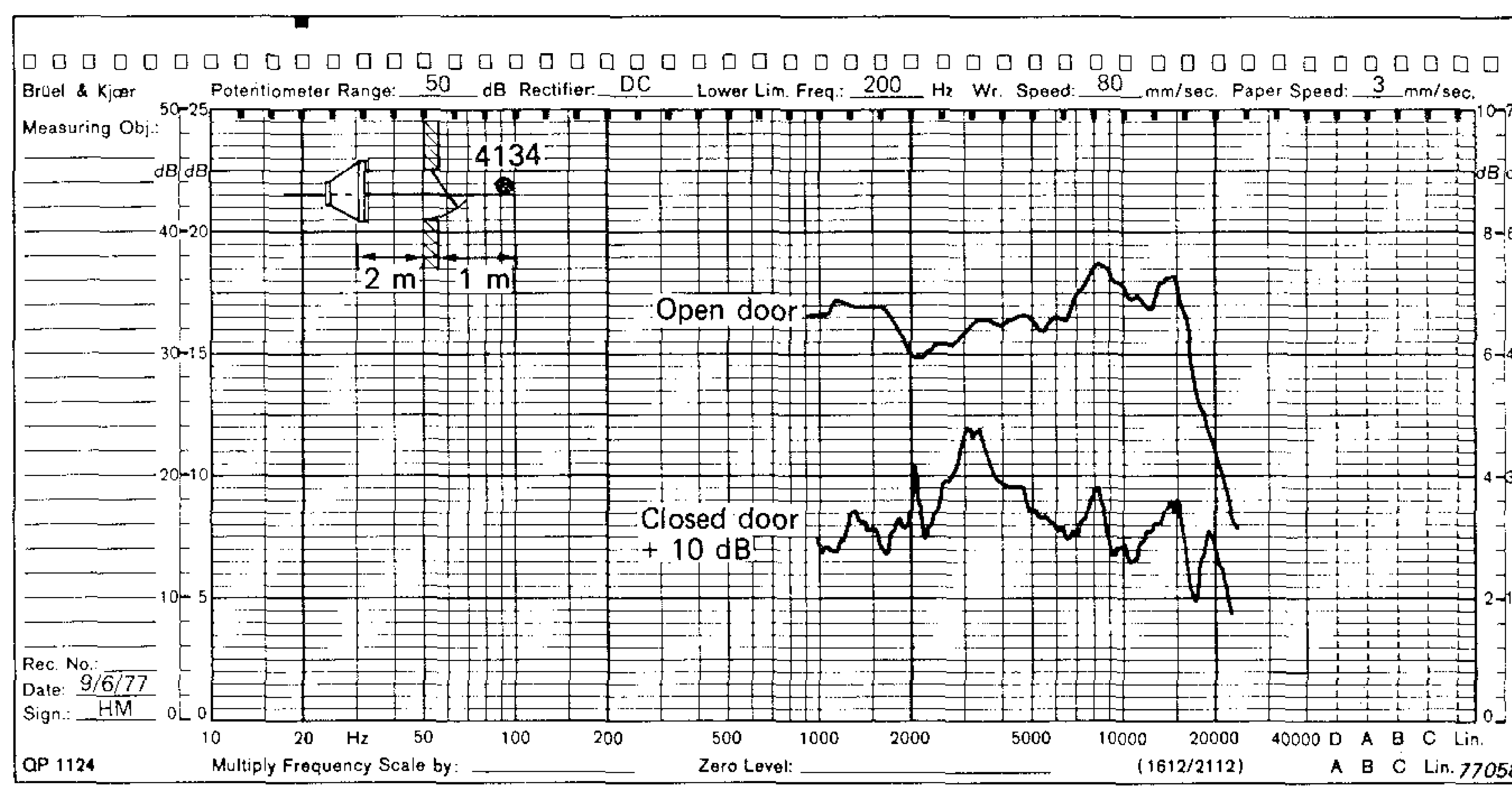

Fig.29. Spectra of conventional door open and closed. On axis

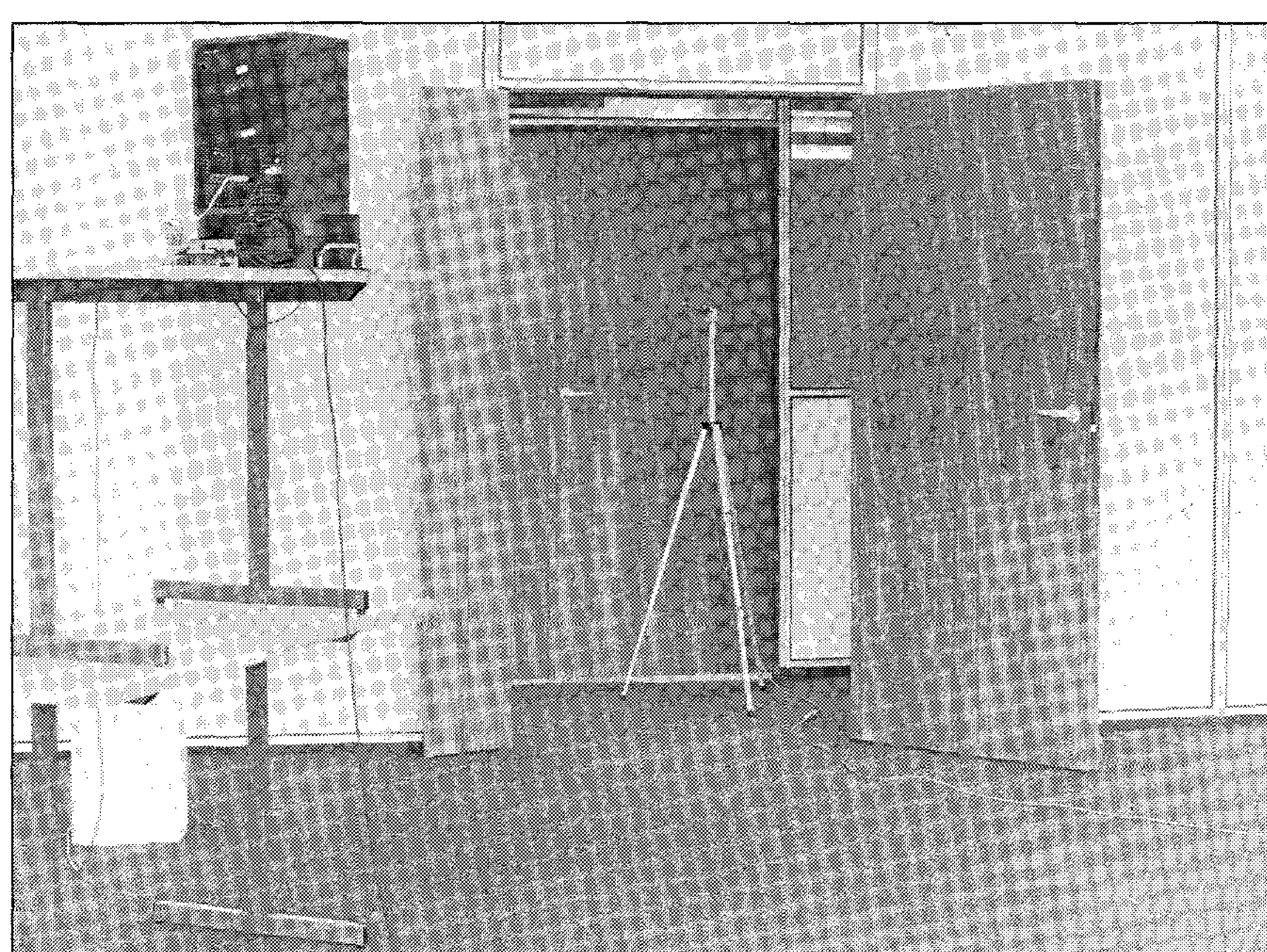

Fig.30. The open door set-up in practice (30° off axis) for measurement of transmission as *function of frequency*

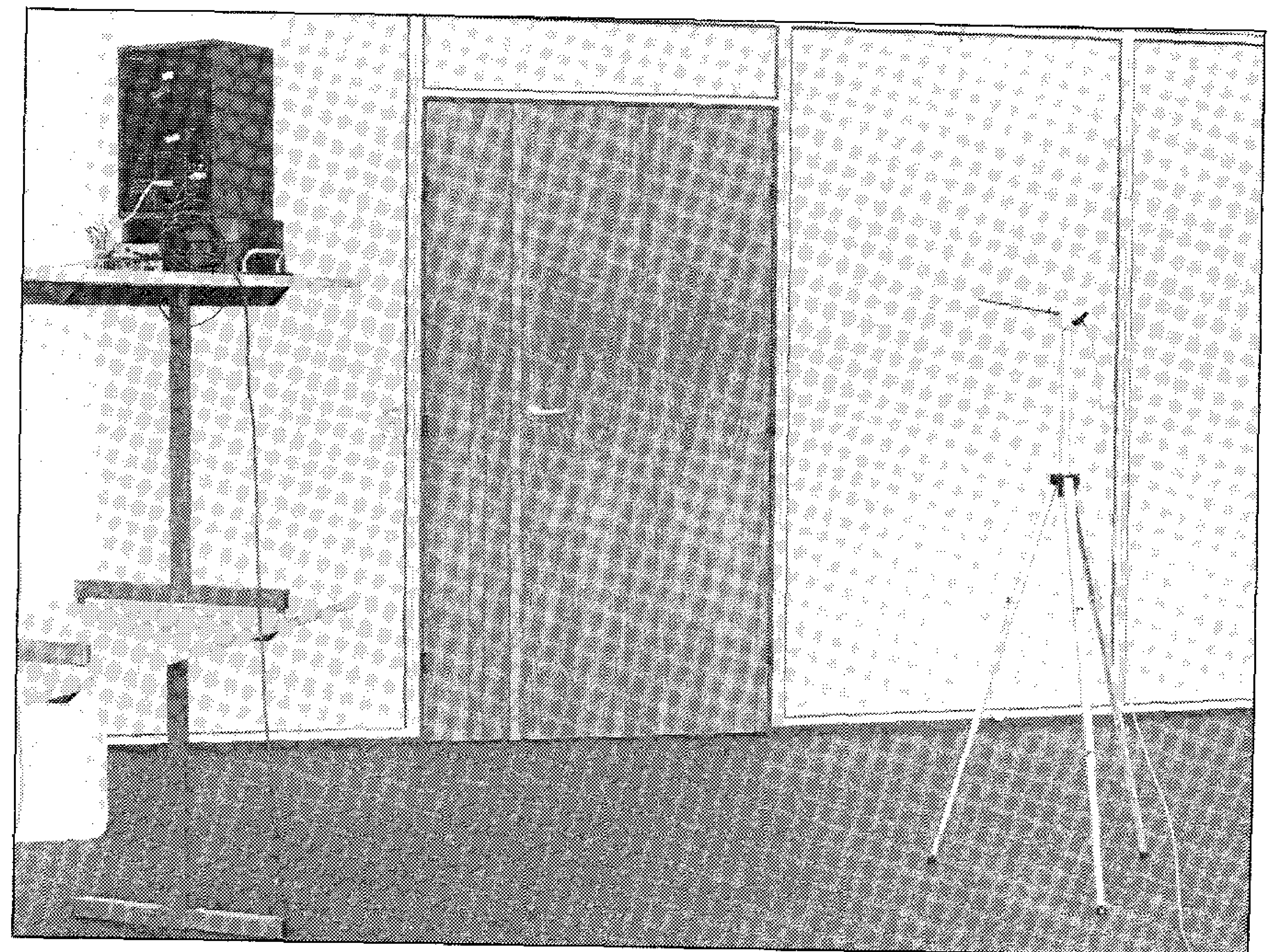

Fig.31. Reflections as functions of frequency can also be measured using gating techniques

10. Conclusion and Applications

This paper has tried to introduce the 3D technique in acoustic and electro-acoustic applications using the new relatively inexpensive calculators with instruments having an IEC interface.

The building acoustic application which is especially emphasized in this paper is useful in concert halls, cinemas, theatres, studios, etc.

The application determining absorption and reflection coefficients as a function of frequency and angle is another important building acoustics parameter.

The early reflections of loudspeakers in 3D is also an extremely important parameter in loudspeaker design, but generally the 3D program can be used for all kinds of plots indicating relations between 3 parameters. A procedure could, for instance, be introduced for 3D displays of Harmonic, Difference Frequency and Intermodulation curves measured with the Heterodyne Analyzer 2010, the Distortion Measurement Control Unit 1902 and a simple external A/D converter (Ref.12). 3 D sound power could also be measured and the list is almost endless.

We will conclude the paper by showing two other possibilities using the 3D plots. Fig.32 shows the 3D reverberation time of the lecture room and Fig.33 shows a 1/12 octave 3D display of the room. There are many other possibilities in the future.

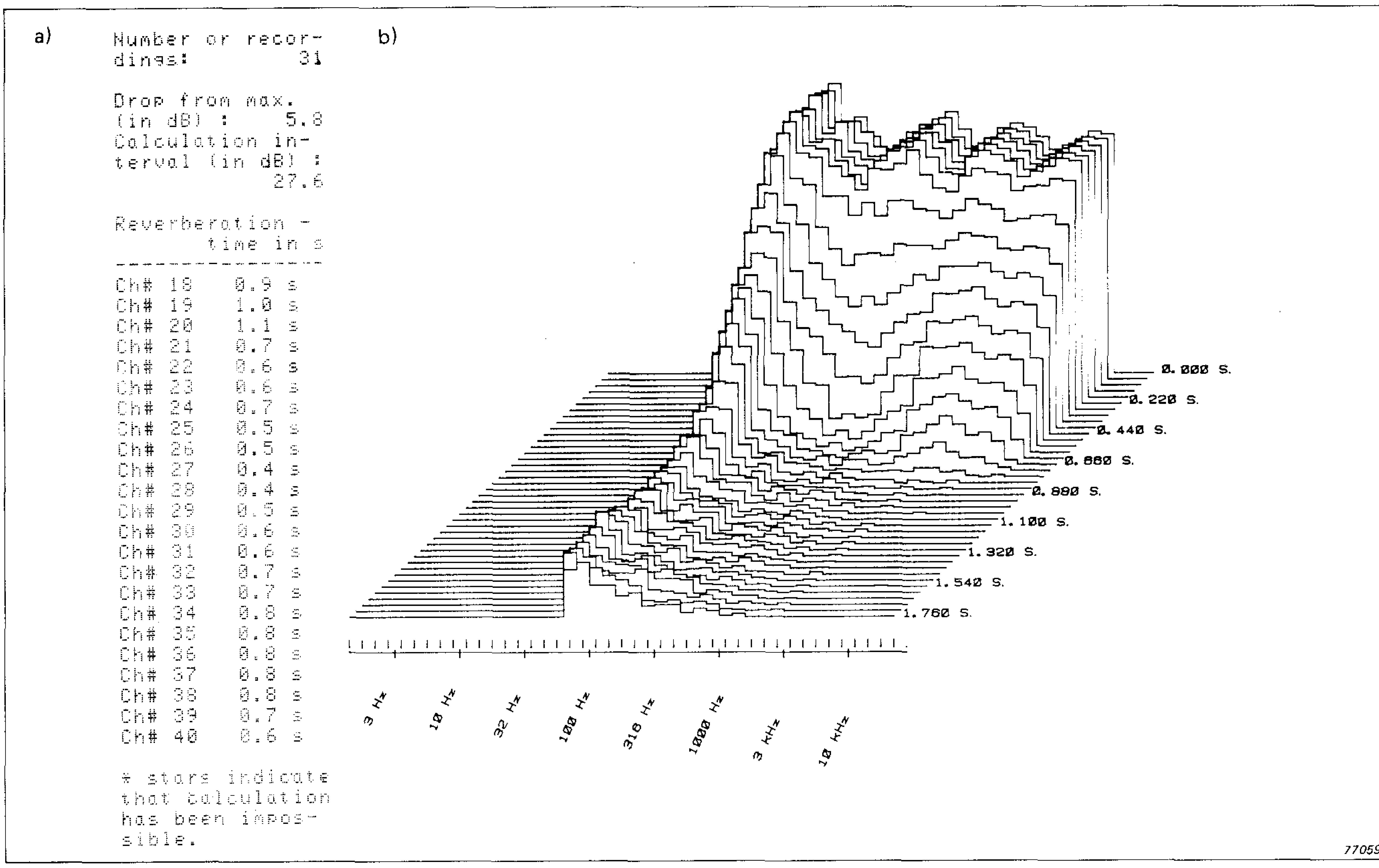

Fig.32. a) Numerical values of the reverberation time in the lecture room
b) 3 D plot of reverberation time in the lecture room

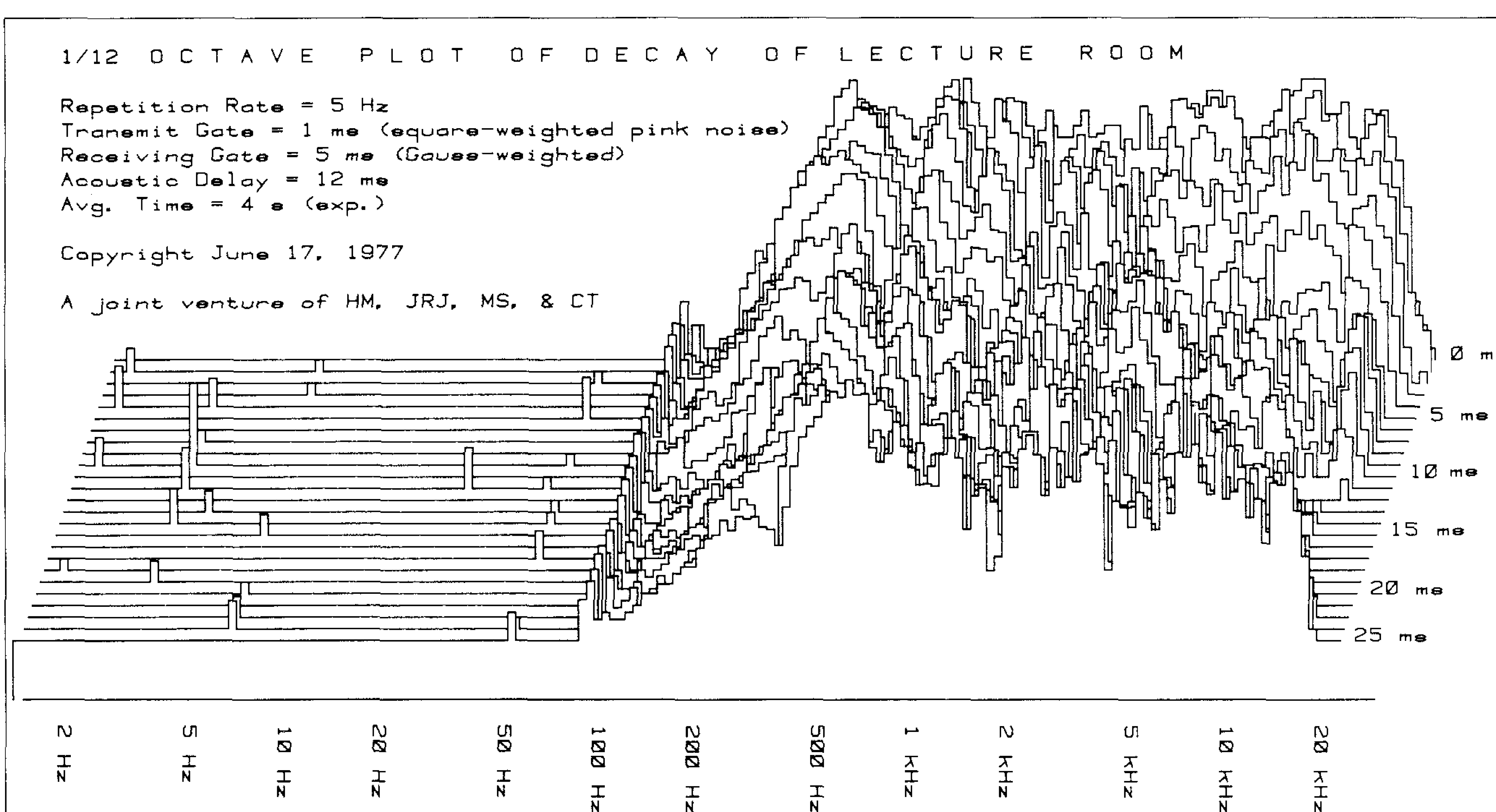

Fig.33. 1/12 octave plot of the decay of the lecture room

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Bob Randall
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B & K Technical Book 1977

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