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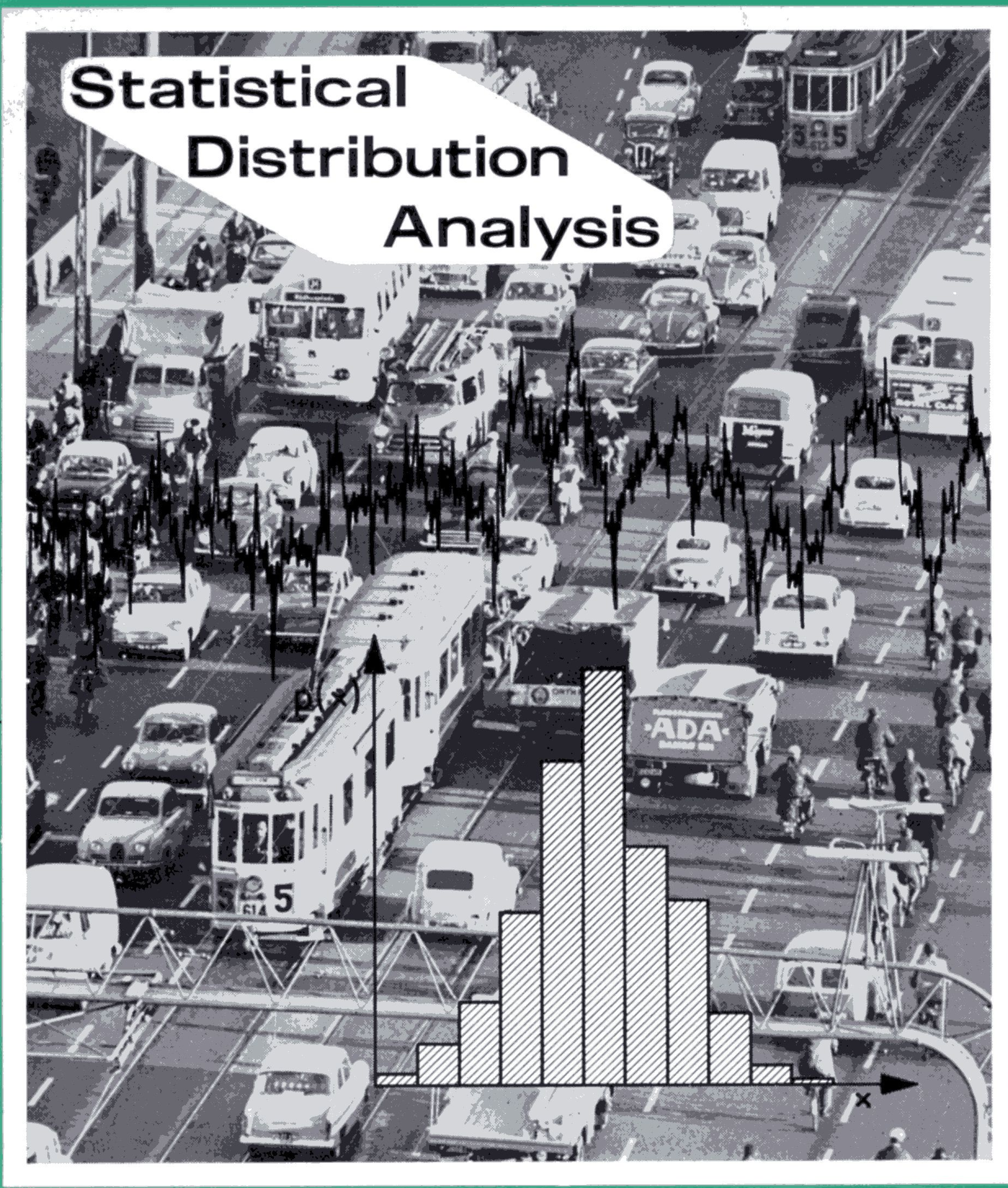

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K. LARSEN & SØN - LYNGBY

Statistical Analysis of Sound Levels

by

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ABSTRACT

The inability of ordinary sound level measurements to give a complete picture of noise of a fluctuating level is pointed out. Such fluctuations are characteristic of most sounds, whether man-made or occurring naturally, so that improved measuring methods are often desirable. An automatic measuring system based on statistical analysis is described in some detail, with a brief mathematical outline of the principles involved. In order to demonstrate the possibilities of such a measuring system a few practical examples are given, in which the noise on a busy street and near an airport runway was analysed. The results of the measurements are given in the form of probability distribution histograms.

SOMMAIRE

Les mesures ordinaires de niveau sonore sont insuffisantes pour caractériser complètement un bruit de niveau fluctuant. Ces fluctuations étant caractéristiques de la plupart des bruits aussi bien artificiels que naturels, il est souvent nécessaire d'avoir recours à des méthodes spéciales de mesure. L'article décrit un système automatique de mesure réalisant l'analyse statistique des signaux ainsi que brièvement les principes mathématiques mis en jeu. Quelques exemples démontrant les possibilités pratiques d'un tel équipement de mesure pour l'analyse d'un bruit de rue ou d'un bruit d'aérodrome sont donnés. Les résultats des mesures sont données sous la forme d'histogrames de distribution des amplitudes probables.

ZUSAMMENFASSUNG

Für die Beurteilung von Geräuschen mit regellos schwankendem Pegel sind statistische Meßverfahren unerläßlich. Der Artikel führt einige Ergebnisse an, welche mit dem Pegelhäufigkeitszähler Typ 4420 bei der Untersuchung von Verkehrslärm und Fluglärm gewonnen wurden. Zuvor werden einige mathematische Grundbegriffe angegeben.

Introduction.

This article describes some interesting new possibilities for ordinary sound level measurements, and points out that it is often quite wrong to accept a single reading on a sound level meter even if this reading is accurate and truly represents the sound level at some position at a specified instant of time.

Getting away from the well-ordered conditions of the laboratory and going out into the field to investigate practically occurring phenomena in the rough and tumble of daily life is of course the way to set about solving environmental problems, but because so many of these phenomena are indeterminate and irregular, their evaluation can pose considerable difficulties. Most investigators have experienced these difficulties trying to average the readings on a sound level meter when the sound measured is not constant. It is these irregular conditions that will be considered here. Sound level is the classic example, though the philosophy is also applicable to such things as mechanical vibration, dynamic strain, and variable quantities in general.

The Meaning of Level.

The term level refers to some descriptive value of a rapidly varying quantity, usually r.m.s., though other values are sometimes used, e.g. peak or absolute average. The statistics of the intrinsic fluctuations in instantaneous value of a signal have been the subject of considerable study, (see B & K Technical Review No. 4-1959, 4-1960, 1 and 2-1961, 4-1962 and No. 3-1963) but are not considered here. We are presently more concerned with variations in the r.m.s. value of a signal. Such variations are exhibited by most sounds whether man-made or occurring naturally.

Instruments for measuring sound levels are designed to emulate the human hearing system which averages out the fluctuations in instantaneous value, and is not therefore aware of the excursions in sound pressure from zero up to perhaps several times the r.m.s. value.

The Need for Statistical Analysis.

Although it may be fortunate for the sufferer that the sounds which must be measured in the field are seldom constant, this fickleness does create measurement problems. As can be seen from Fig. 1, which is a continuous record of the total sound pressure level on a busy street in Copenhagen, it is quite meaningless to quote a sound level as measured with a sound level meter at a single instant in time. The sound level varies with time over at least 15 dB, and the only proper description of the events seems to be statistical.

Because they wanted to be on the spot at all instants of interest, acoustic experts have been reported, perched high above the roaring traffic in the night, peering at meter scales with the patience and vigilance usually characteristic of bird photographers.*) Of course the physical discomfort

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*) See for instance L. N. Miller: "A Sampling of New York City Traffic Noise", Noise Control 6, 3. p. 39 (1960).

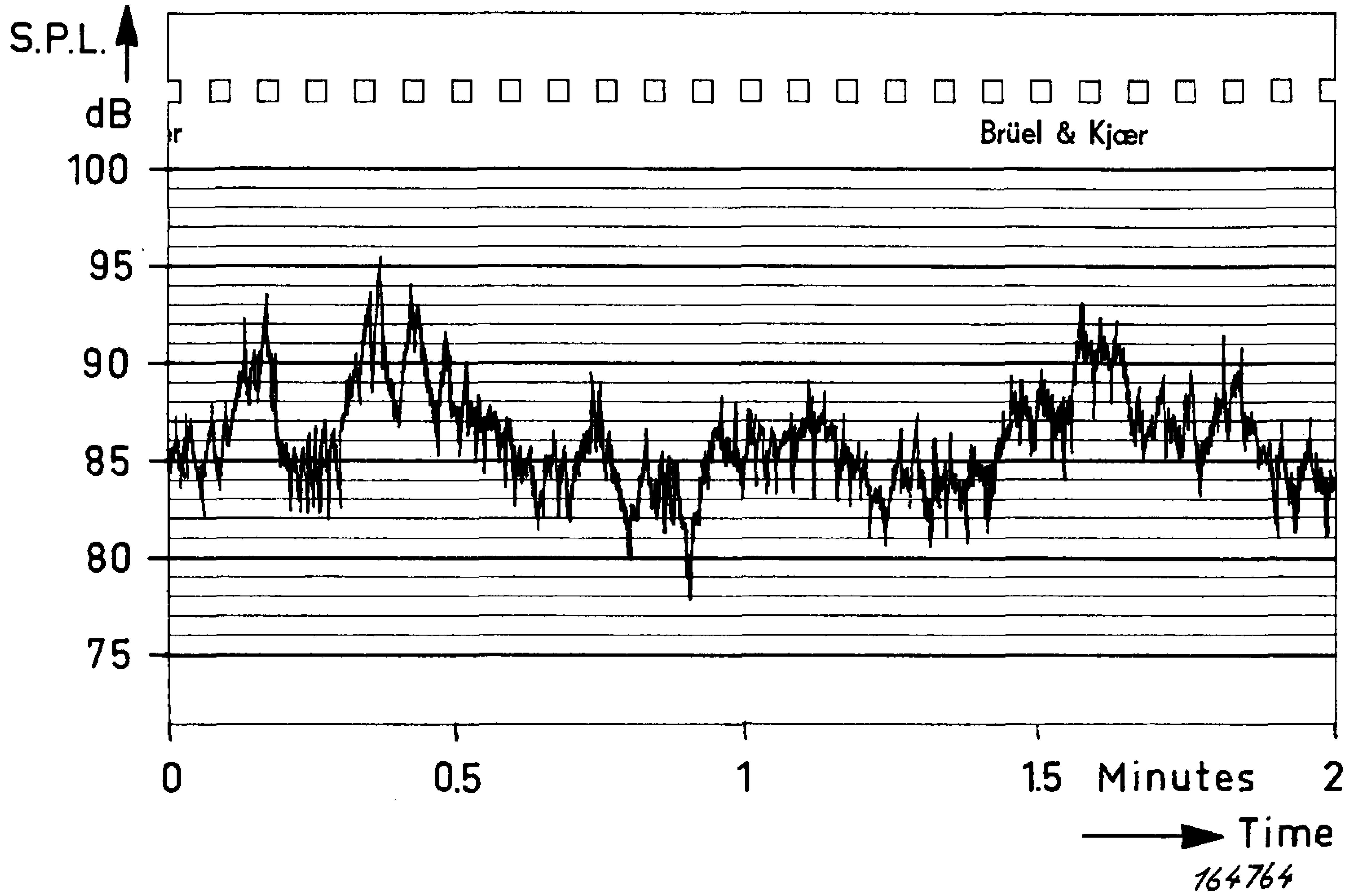

Fig. 1. Recording of overall sound pressure level on a busy street in Copenhagen.

associated with such investigations can be alleviated by employing an automatic level recorder to obtain the sound level as a function of time, but even then considerable effort must be spent in the interpretation of the records.

The evaluation of hearing damage risk is usually based on measurements taken with a sound level meter at a position in a factory, in a ship's engine room etc., where hearing damage might be anticipated. Much research has gone into this problem and a number of curves and procedures have been published for relating sound level and exposure time to probable hearing loss. These procedures do, however, usually refer to noises of steady level. Little work has been done on the problem of such evaluations in case of fluctuating sound levels, but since most noises encountered in practice have an irregular nature, it seems desirable that procedures should be worked out for taking these fluctuations into account. It is not sufficient to work with an average value of the sound level since high peaks of short duration which would not necessarily show up in the average figure can be very damaging to the hearing mechanism.

Heretofore it has been usual practice to conveniently ignore the effects of level fluctuations in the evaluation of hearing damage risk etc., mainly because of the disproportionately large amount of work involved in determining the magnitude distribution of sound levels both in setting up the initial criteria and in the subsequent use of these.

The Statistical Distribution Analyzer Type 4420.
An excellent instrument for the determination of the statistical properties of noise level fluctuations has been brought on the market by Brüel & Kjær, which makes possible a new approach to sound level measurements. The tedious and time consuming process of analysing level recordings on paper can be obviated in a raliable and versatile manner by coupling a B & K Statistical Distribution Analyzer Type 4420 to the Level Recorder Type 2305. See Fig. 2.

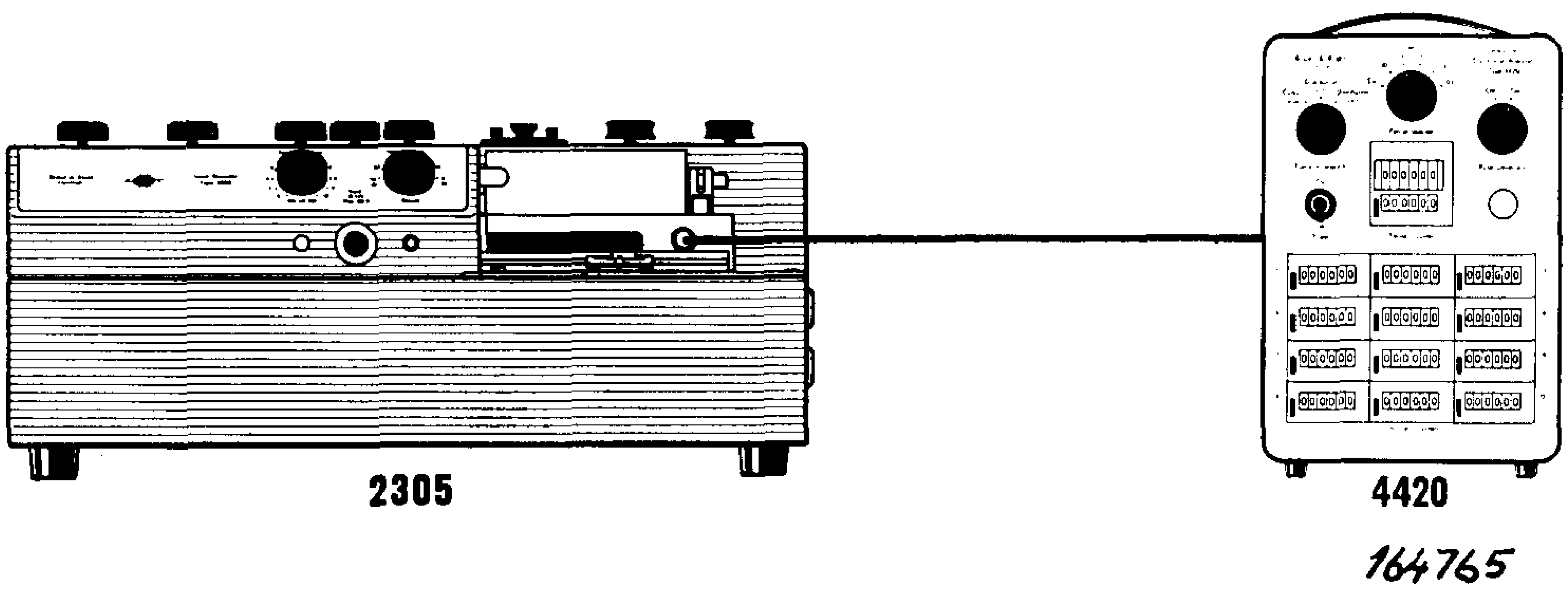

Fig. 2. The Statistical Distribution Analyzer connected to the Level Recorder.

The Statistical Distribution Analyzer includes a set of twelve contacts which are scanned by means of the writing arm of the level recorder, thus enabling the recorded information to be resolved in twelve bands and a numerical display of the data presented on a set of counters. Should a time chart be required from the recorder, this can be run off simultaneously.
The pulses driving the counters originate from a generator with variable pulse repetition periods of o.1, o.3, 1, 3 or 10 seconds. One counter registers the total counts, while each of the other twelve counters is normally only in operation when the relevant contact on the recorder is made. All the counters run up to 999,999 which means that even with the shortest pulse repetition period the apparatus can run for 24 hours. There is a window in which a suitable target figure can be set, and when the total register reaches this figure, counting stops automatically.
When the Distribution Analyzer is used with the Level Recorder there are two modes of counting: "Distribution — 2305" and "Cumulative". The former is perhaps the most usual mode of operation. In this case only that counter which corresponds to the position of the contact arm on the level recorder will count, so that a twelve step histogram can be drawn up from the numbers indicated by the counters. Logic circuits ensure that

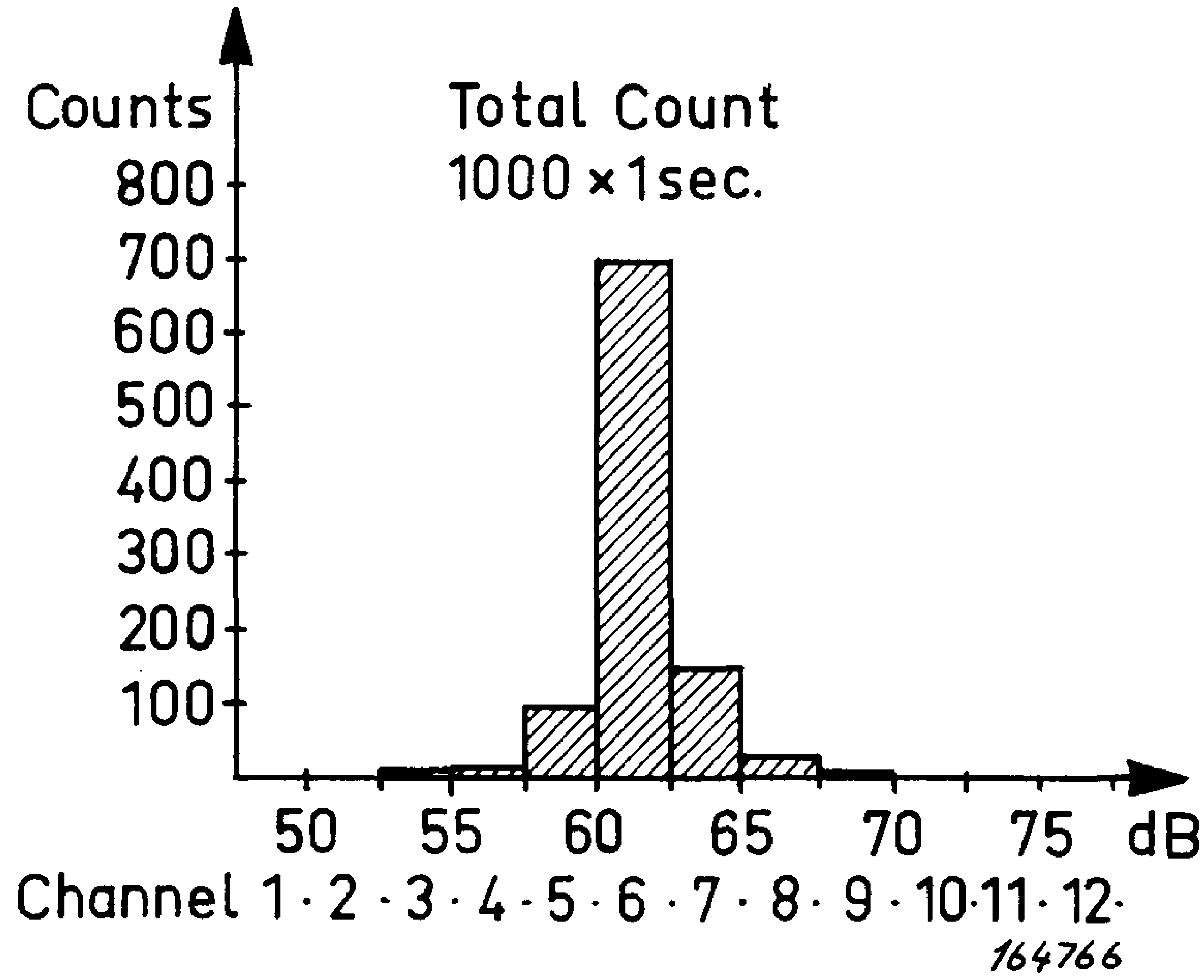

Fig. 3. Statistical distribution of sound level in a typist's office. The percentage of time for which the sound level lies between 60 and 62.5 dB is 70 %.

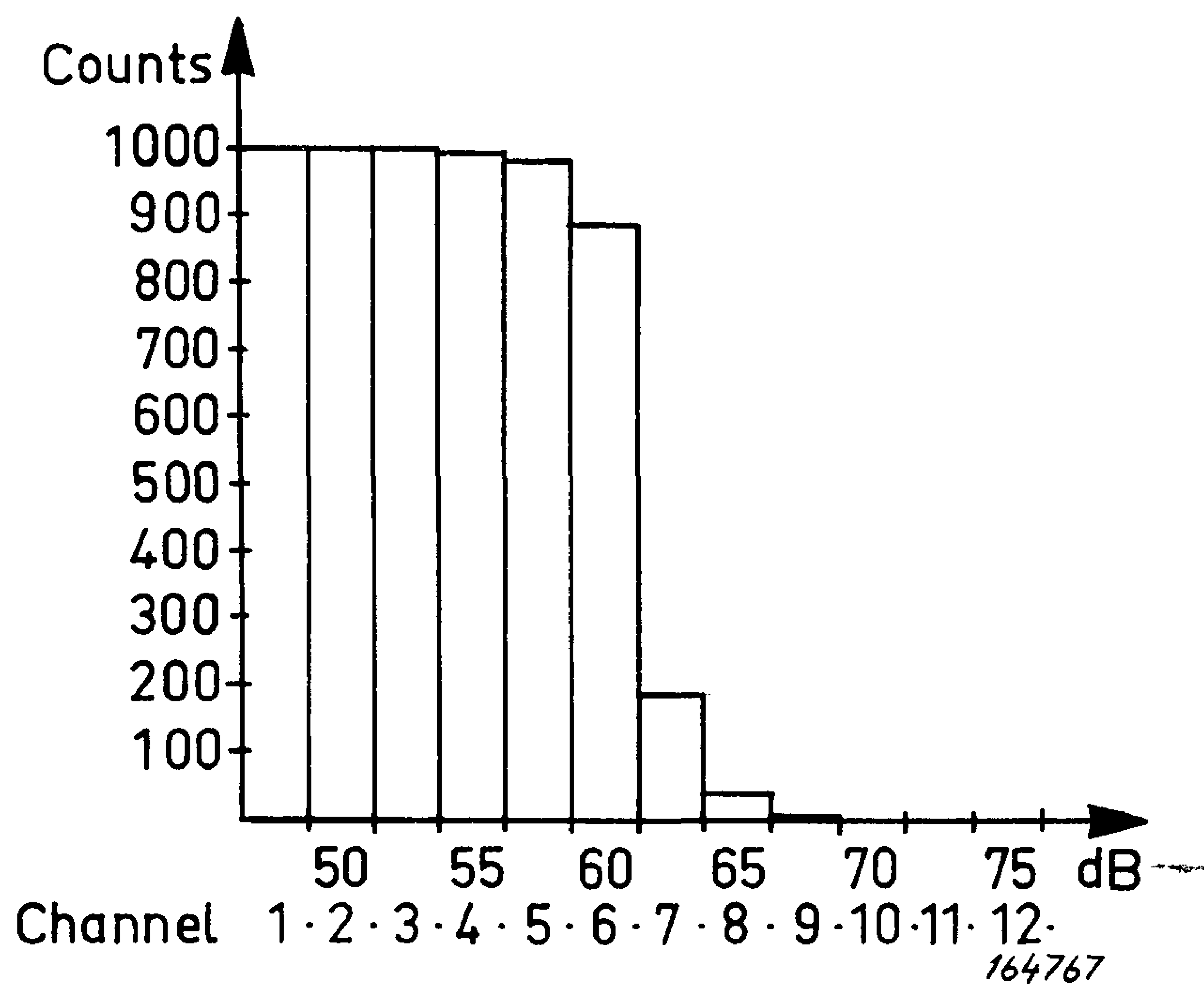

Fig. 4. Cumulative plot of sound level distribution in a typist's office. The percentage of time for which the sound level is higher than 60 dB is 85 %.

only one channel counter registers in case the contact arm should be situated exactly in the middle between two adjacent contacts at the time of count. The sum of all the channel readings equals the total figure, so that if a suitable power of 10 is set as a target, the percentage of time for which the recorded level lies within certain narrow ranges can be read off immediately. See Fig. 3.

By addition it would be possible to say from the histogram for what period of time the level exceeded a particular value.
This addition process can be carried out electronically when the function switch is on "Cumulative", and the corresponding curves can be plotted directly from the figures indicated by the counters. Such a curve is shown in Fig. 4.

Matematical Basis.
DISTRIBUTION CURVES
Consider a time plot showing the level variations of a signal as shown in Fig. 5.
The probability that the level lies between x and x + Δ x is given by

$$P(x, x + \Delta x) = \frac{\Sigma \Delta t_n}{T} = \frac{\Delta t_1 + \Delta t_2 + \ldots + \Delta t_n}{T} \quad \ldots 1$$

assuming that the process from which the signal is derived is stationary and that the sampling time T is long enough*).

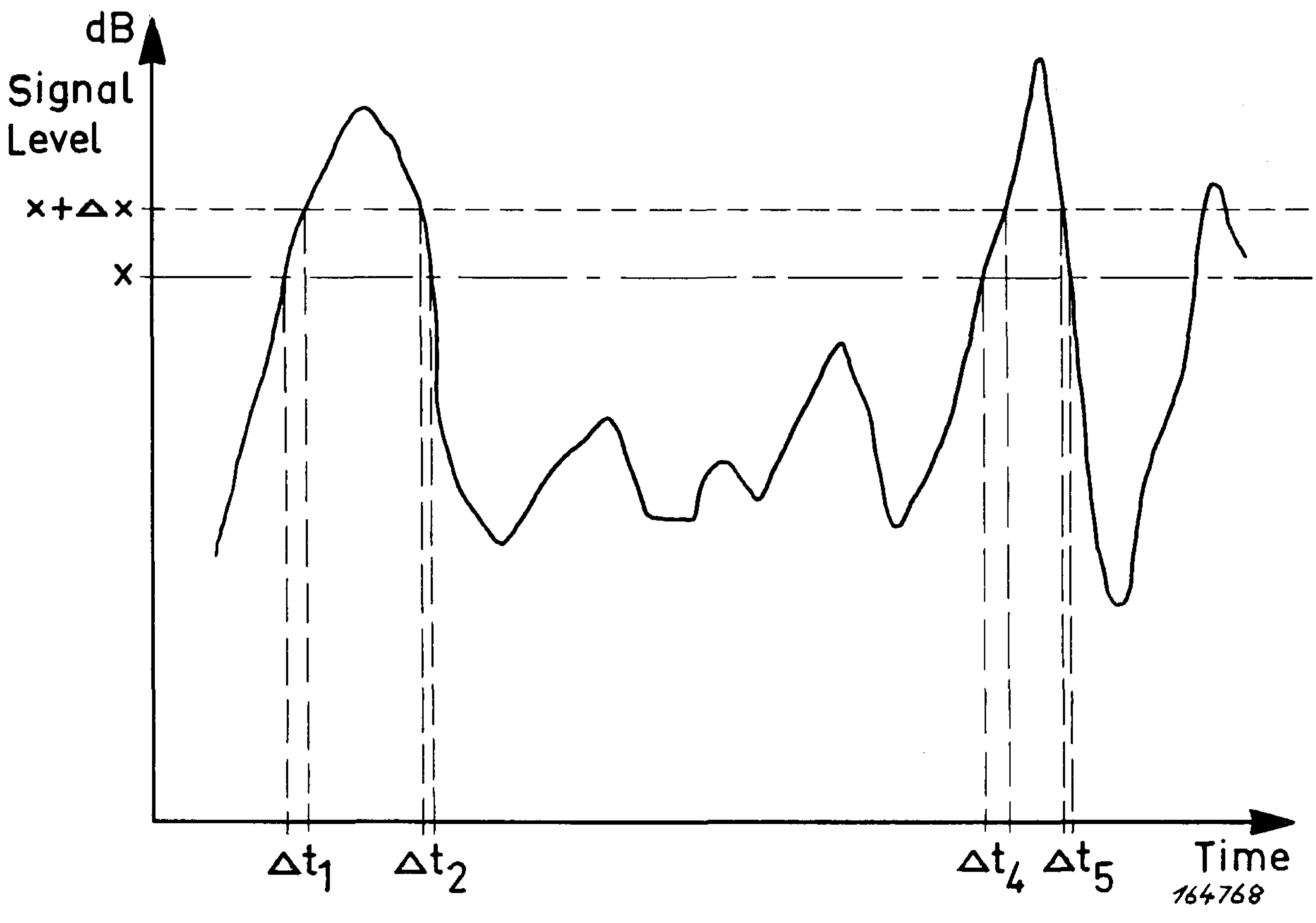

Fig. 5. Variation of signal level with time.

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*) Readers requiring more information about probability and statistics are referred to one of the excellent textbooks on these subjects.

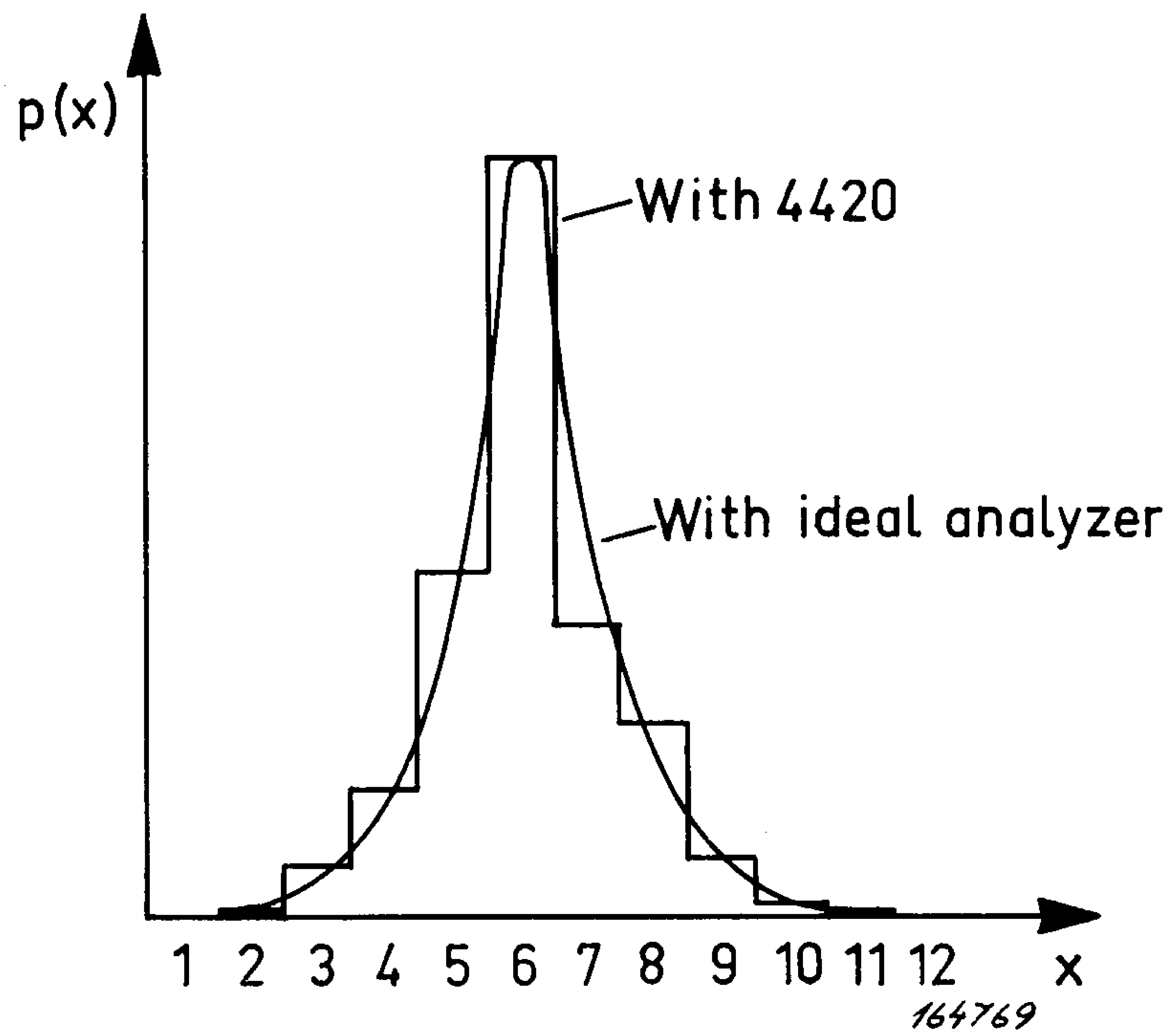

Fig. 6. Probability density curve as obtained with the Statistical Distribution Analyzer and the same curve as given by an ideal analyzer of infinite resolution.

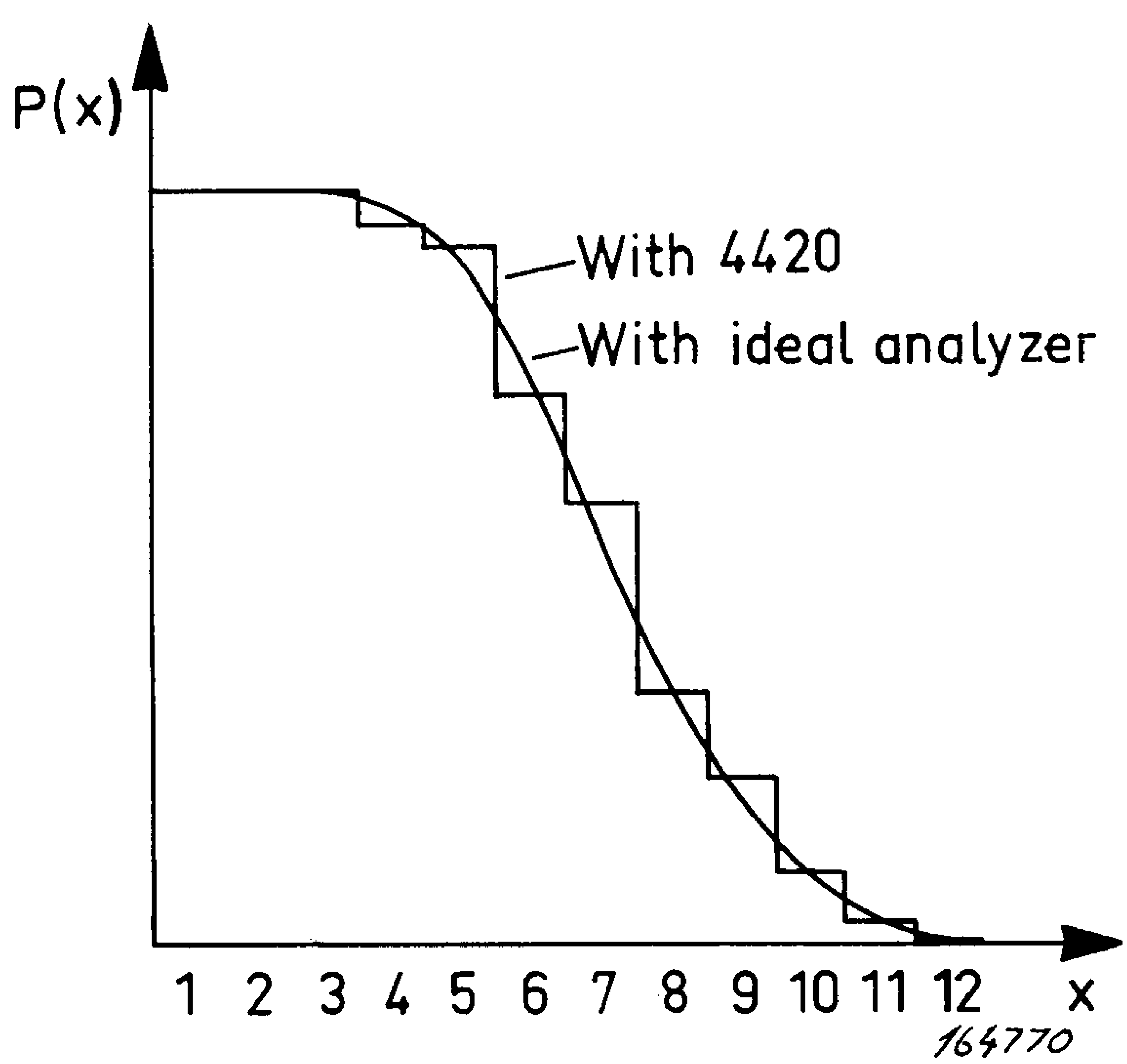

Fig. 7. Cumulative plot obtained with the Statistical Distribution Analyzer compared with the same information obtained with an ideal analyzer of infinite resolution.

Smooth curves such as the Normal Gaussian Distribution Function are actually "probability density" plots, i.e. they show the probability per unit x taken over a very narrow Δx:—

$$p(x) = \lim_{\Delta x \to 0} \frac{P(x, x + \Delta x)}{\Delta x} \quad \ldots 2$$

In plots made from readings on the Statistical Distribution Analyzer Δx is finite; it represents 1/10 of the range covered by the potentiometer used with the Level Recorder.*)

This means that a stepped plot results, instead of the smooth curve which would be given by an analyzer of infinite resolution. See Fig. 6.

Returning to equation 1, if Δx were made wider so as to encompass all values above a certain x, the probability that the level exceeds x would result.

This can be regarded as a summation over many standard Δx widths, and is the principle on which the Statistical Distribution Analyzer is working when switched to "Cumulative". Plots obtained this way are similar to Fig. 7. Once again the stepped version represents a good approximation to the ideal curve given by integration over the ideal curve of Fig. 6.

The same amount of information is contained in the two kinds of presentation (i.e. Fig. 6 and Fig. 7). In fact one is the summation — or in the limiting case, the integral — of the other:

$$P(x)_{\text{FIG. 7}} = \sum_{x = n}^{x = 12} P(x_n)_{\text{FIG. 6}} \qquad \text{or}$$

$$p(x)_{\text{FIG. 7}} = \int_{x}^{\infty} p(x)_{\text{FIG. 6}}\, dx$$

Nevertheless plots similar to Fig. 6 give the data in the manner which lends itself best to further statistical analysis. The smooth curve is, as already stated, a Probability Density Curve while the stepped plot will be referred to as a Probability Distribution Histogram, not be confused with the stepped Cumulative Probability Plot of Fig. 7.

*) Potentiometers available for the Level Recorder cover dynamic ranges of 75 dB, 50 dB, 25 dB, 10 dB logarithmic and 10—35 mV or 10—110 mV linear.

MEAN VALUE AND STANDARD DEVIATION

A normal (Gaussian) random variable is completely specified by its *mean value* and *standard deviation.* When the quantity measured is an outcome of many independently varying phenomena, such as the sound pressure level in a busy street, the distribution is approximately Gaussian in character so that the mean value and standard deviation give a good description of this quantity.

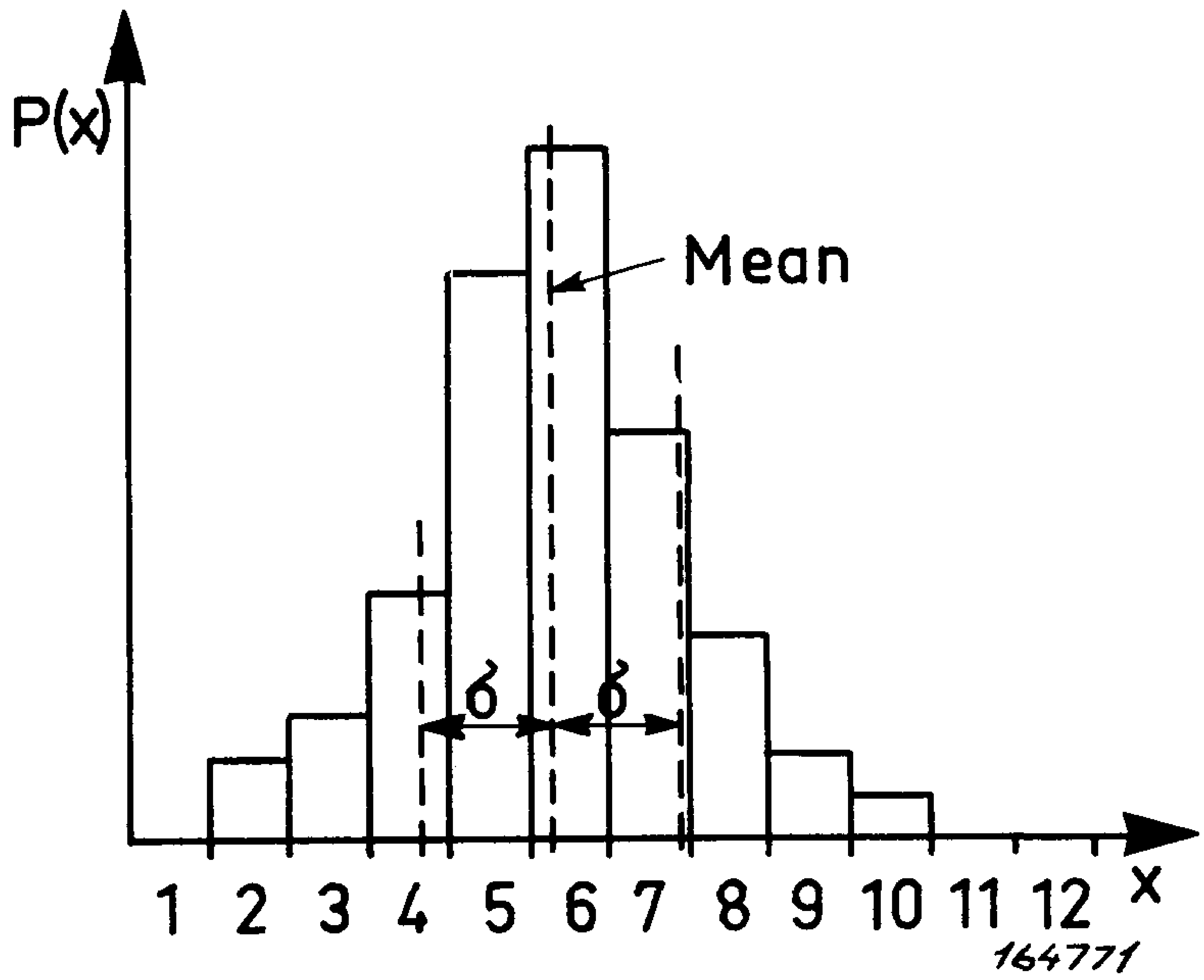

Fig. 8. Example of distribution histogram showing mean value and standard deviation.

Focussing our attention now on the probability distribution histogram, it is quite simple (if slightly laborious) to work out for each practical case the various moments of the distribution. The first moment gives the mean value of the signal being analysed, corresponding to the axis of the centre of gravity of a flat plate cut out to exactly the same shape as the histogram, while the second (central) moment gives the variance of the signal around this mean. The standard deviation, which is the square root of the variance, analogous to the radius of gyration of the plate about its centre of gravity, has become the accepted measure of variability.

Mathematically the mean value, M, and standard deviation, σ, are expressed as:—

$$M = \sum_{x=0}^{\infty} x \, P(x) \text{ and}$$

$$\sigma = \sqrt{\sum_{x=0}^{\infty} x^2 \, P(x)}$$

In Fig. 8 is given a typical probability histogram with values for M and σ calculated.

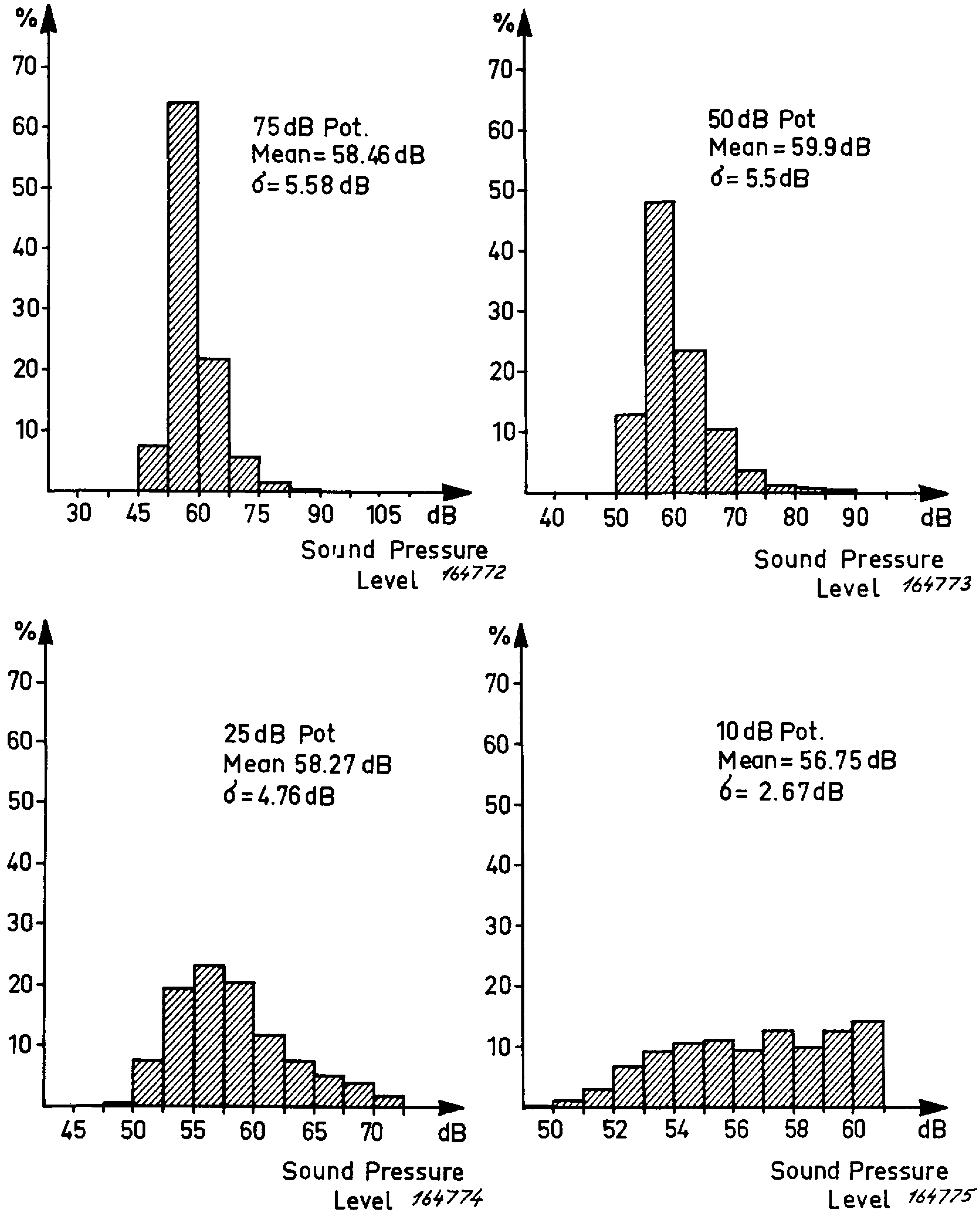

Fig. 9. The statistical distribution of sound pressure level in an office using different range potentiometers with the Level Recorder.

Accuracy.

Best accuracy is obtained when the potentiometer range of the Level Recorder has approximately the same width as the maximum level fluctuations of the signal to be investigated.

In Fig. 9 are given four plots of the sound level in an office obtained with different potentiometers measured over periods of 15 minutes.

It is obvious that the 75 and 10 dB potentiometers should not be used in this case while the 50 and 25 dB ranges are acceptable. The 25 dB range is usually found to be the most suitable for analysing varying sound levels in offices, workshops, for traffic noise etc.
On the following pages will be described in some detail two investigations which were carried out in order to show the usefulness of the Statistical Distribution Analyzer Type 4420. It is not the purpose of these examples to revolutionize sound level measurements or to change existing procedures, but rather to show how a certain amount of time consuming effort can be taken over by an automatic measuring set-up. Many long-time investigations of variable phenomena can be conveniently performed with the Statistical Distribution Analyzer on the same principles as shown in these examples.

Traffic Noise.

In modern, industrial countries many persons must live and work in environments that contain undesired sounds. Sounds are by-products of the mechanized operations that characterize modern industries. Factories, railroads, streetcars, trucks, buses, automobiles, airplanes, and their accessories are accepted as essential to modern industry and modern living. All these machines and many others continuously radiate acoustic energy in their immediate vicinity. The acoustic energy is widely distributed by propagation in air, so that residential and business areas may be filled with sounds which originated from a variety of more-or-less distant sources. In most cases all these sounds are unwanted, and the human being will therefore regard them as noise.
When the noise level exceeds some 85—90 dB re. 2×10^{-4} μbar ~~for~~ a long period of time, the noise may cause hearing loss, as well as influence the human psyche.
Furthermore, the noise level in daily life seems to be steadily increasing due to the increase in numbers of motorized vehicles, and an effective noise control has therefore become more and more necessary. To perform such a control, noise measurements must be made and averages as well as statistical distributions around these averages determined.
Fig 10 shows an example of how the traffic noise level has increased in the later years. In the figure are shown the results of statistical noise investigations in two German towns. The broken line gives the measured result in Berlin 1938 while the other is measured in Düsseldorf 1952.

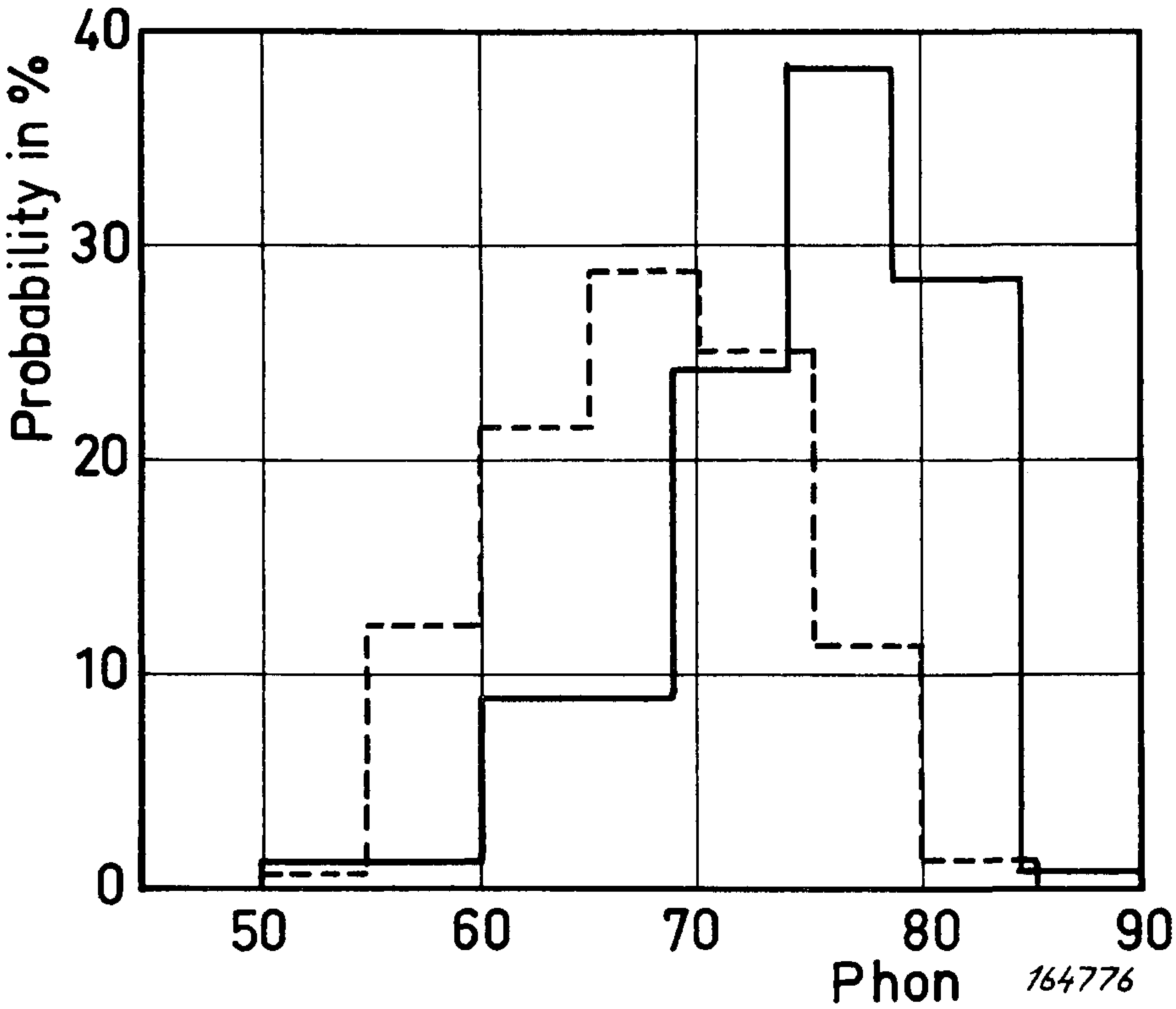

Fig. 10. Histogram of noise levels measured in 1938 and 1952 ("Zeitschrift VDI" vol. 95 page 373).

The abscissa is calibrated in DIN-phon*), and the ordinate in probability. The average noise level in Berlin 1938 was 65—70 DIN-phon, while the most frequent noise level in Düsseldorf 1952 was 75—80 DIN-phon. This is an increase in average noise level of 10 DIN-phon, but, what may be even more important is, that while the noise level of 80—85 DIN-phon took place only 2 % of the sampling time in 1938, this figure has increased to 28 % (14 times higher) of the sampling time in 1952.

In order to give a picture of the traffic noise level nowadays, some statistical noise measurements were made in Copenhagen in October last year. The arrangement used for the measurement is shown in Fig. 11. The position of measurement was in one of the main streets of Copenhagen, and the microphone was placed on the pavement on a tripod.

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*) In accordance with the German DIN 5045, DIN-phon is used as a physical measure for loudness evaluation.

When measuring DIN-phon a weighting network, which for some time was assumed to simulate the frequency weighting of the human ear, is inserted in the measuring circuit. Various weighting networks are used for various sound pressure levels, and the weighting networks 1 and 2 recommended in DIN 5045 resemble the international B and A (IEC) weighting networks respectively.

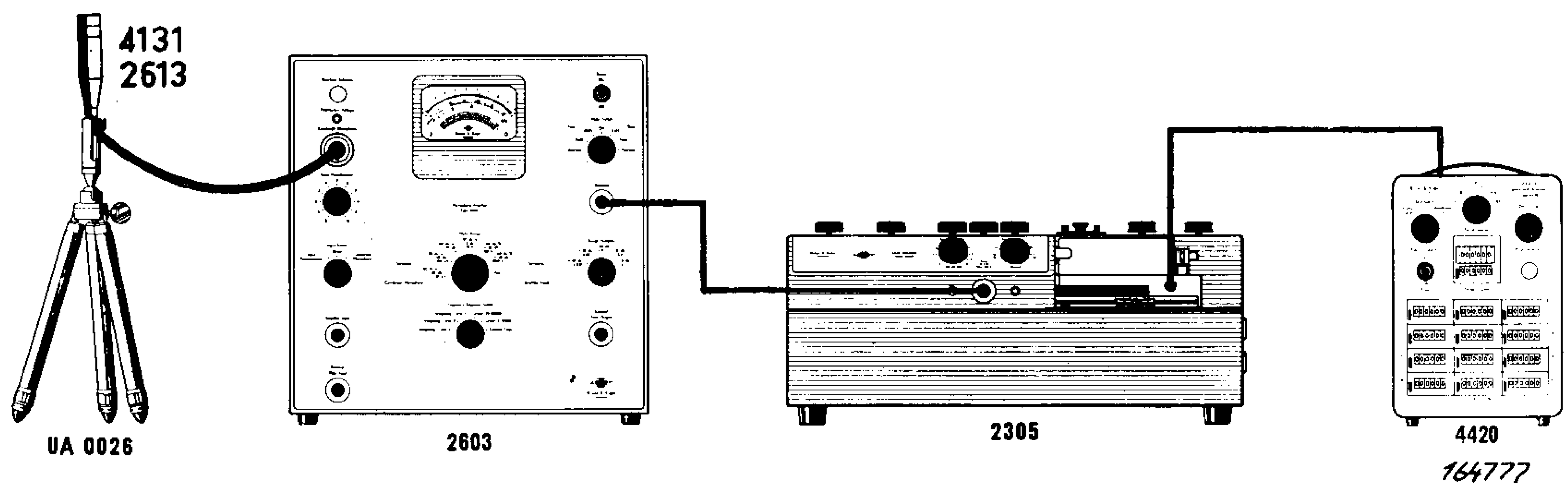


Fig. 11a. Typical measuring set-up used for statistical distribution analysis of traffic noise.

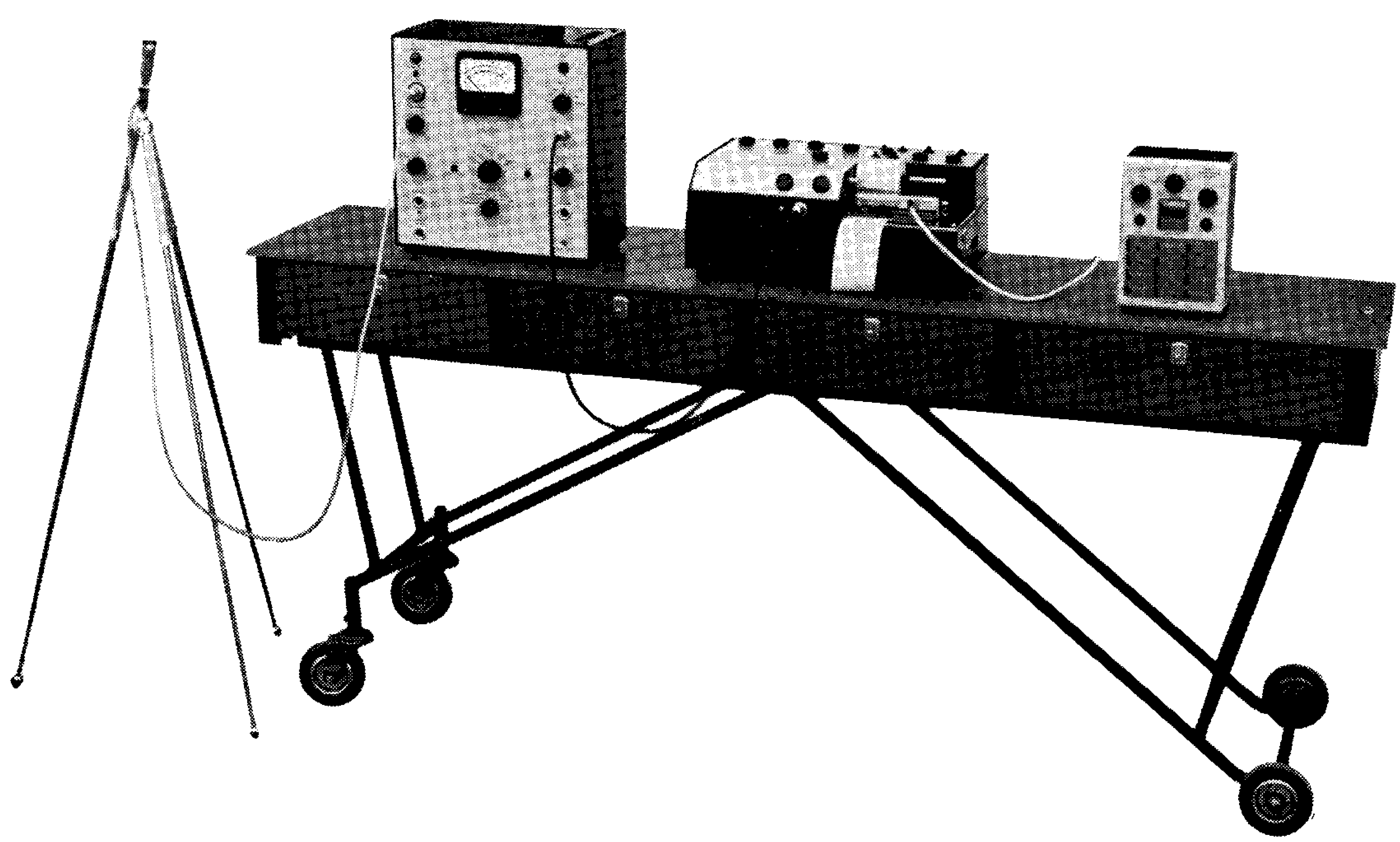


Fig. 11b. Photograph of practical measuring set-up corresponding to Fig. 11a.

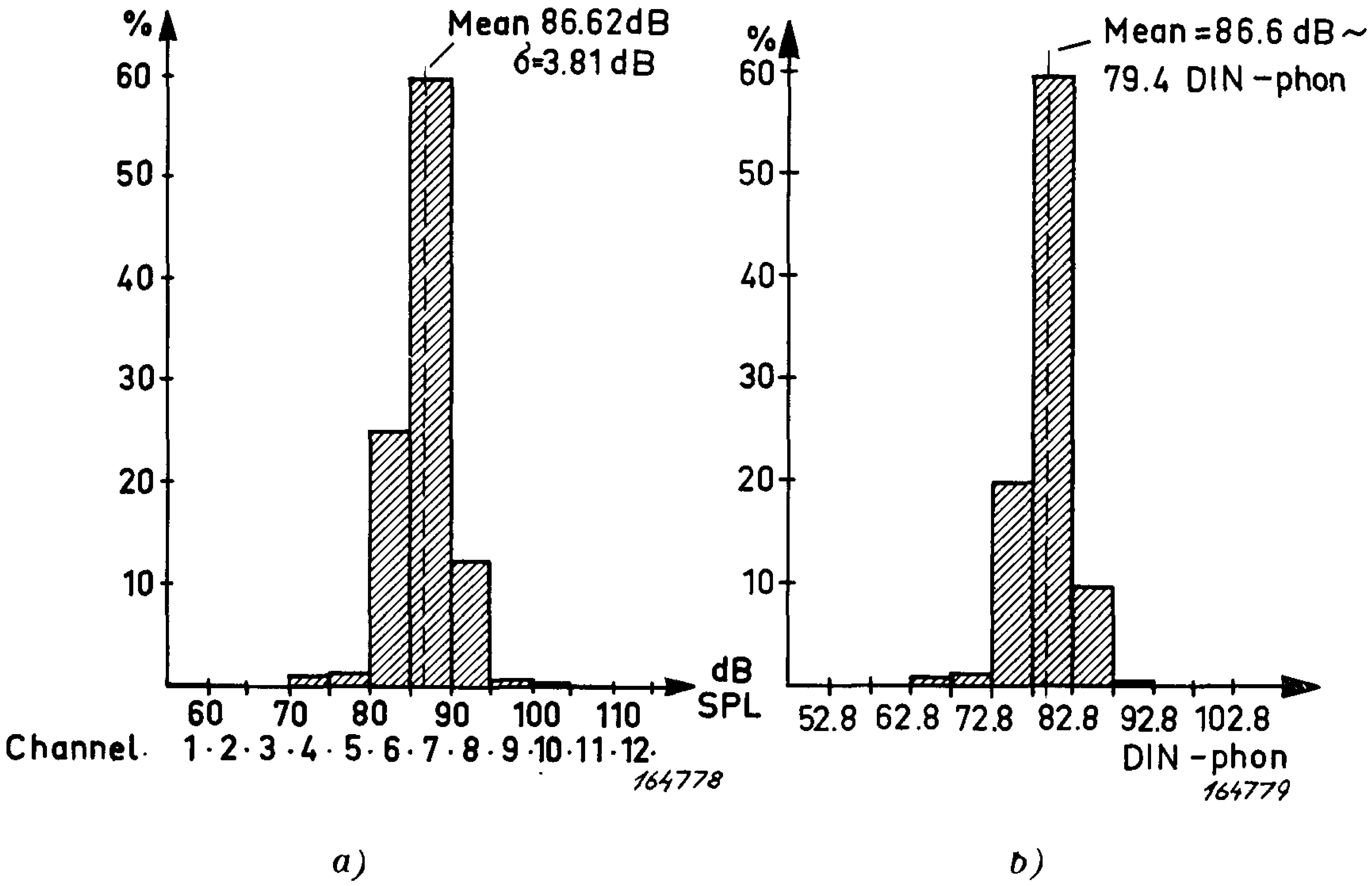


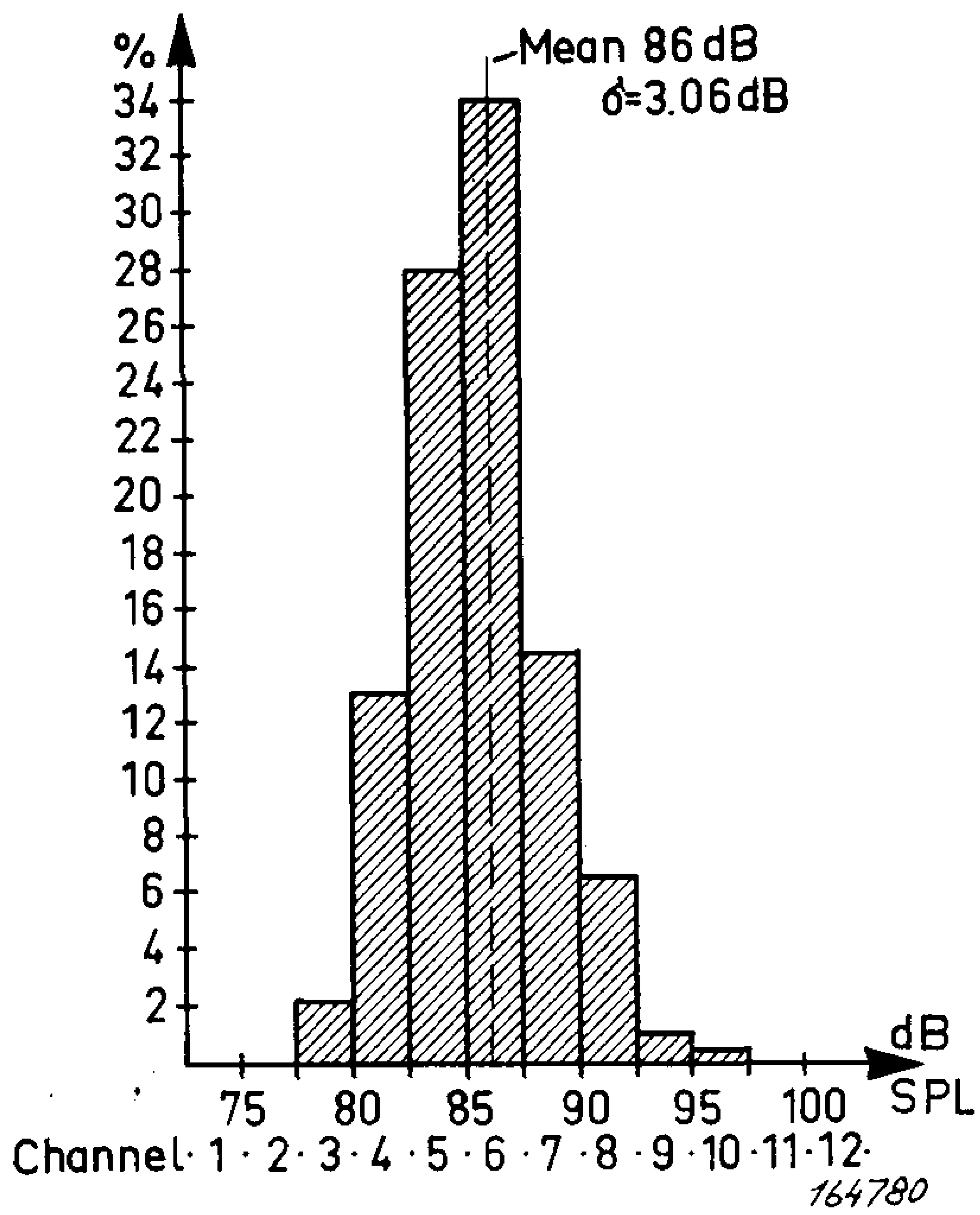
Fig. 12a. Histogram obtained from 2.30 p.m. to 4.10 p.m.
b. The same curves as in Fig. 12a but the abscissa is now changed to DIN-phon.

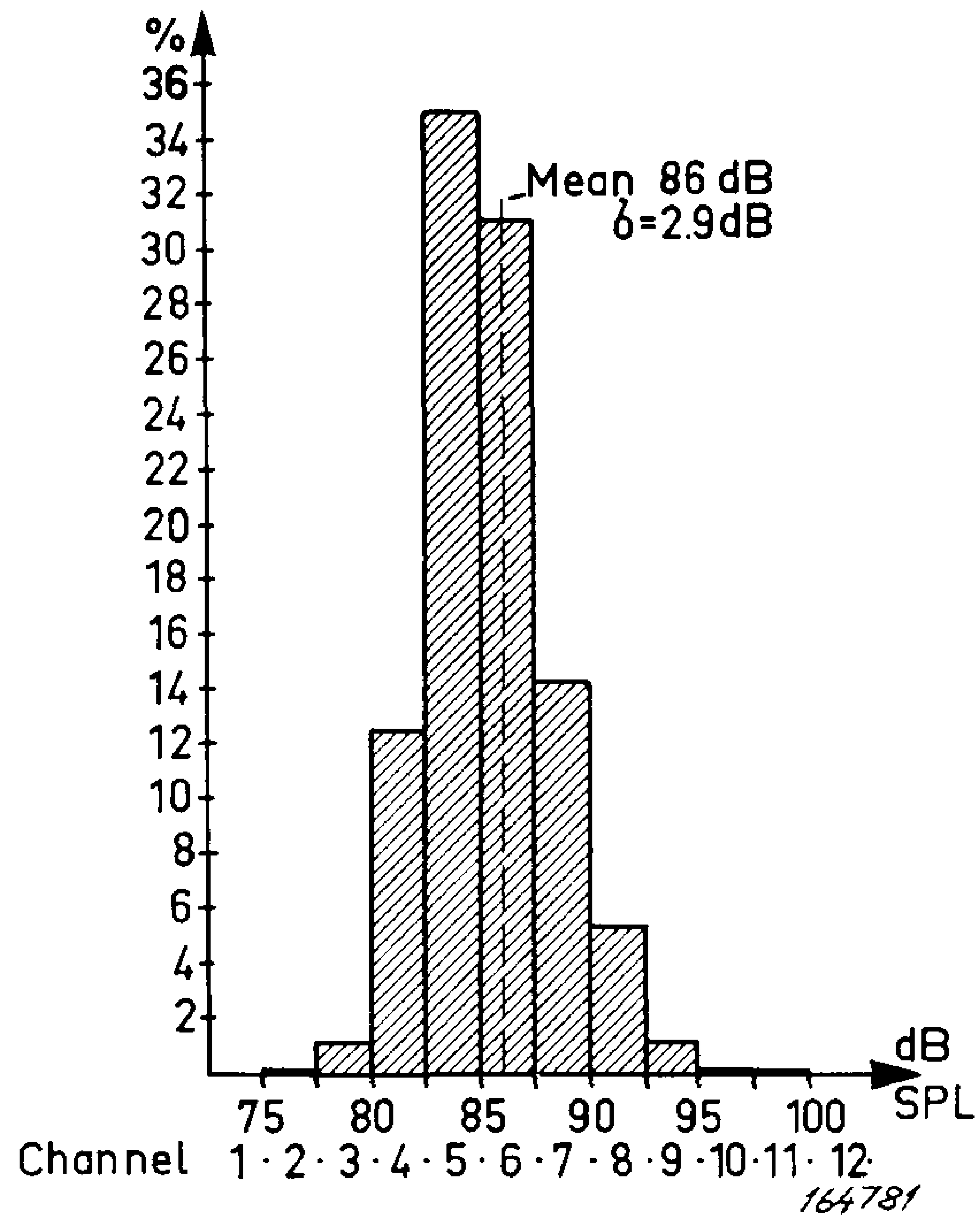
Two different sampling times were used, 100 min. and 15 min., and one curve was measured from 2.30 p.m. to 4.10 p.m. (100 min.). Seven curves were measured with a 15 min. sampling time from 2.15 p.m. to 4.15 p.m. The curves are all shown in Figs. 12a and 13. The dynamic range of the level recorder for the curve shown in Fig. 12a was 50 dB, while the potentiometer range for the curves given in Fig. 13 was 25 dB. The Microphone Amplifier was switched to "linear".

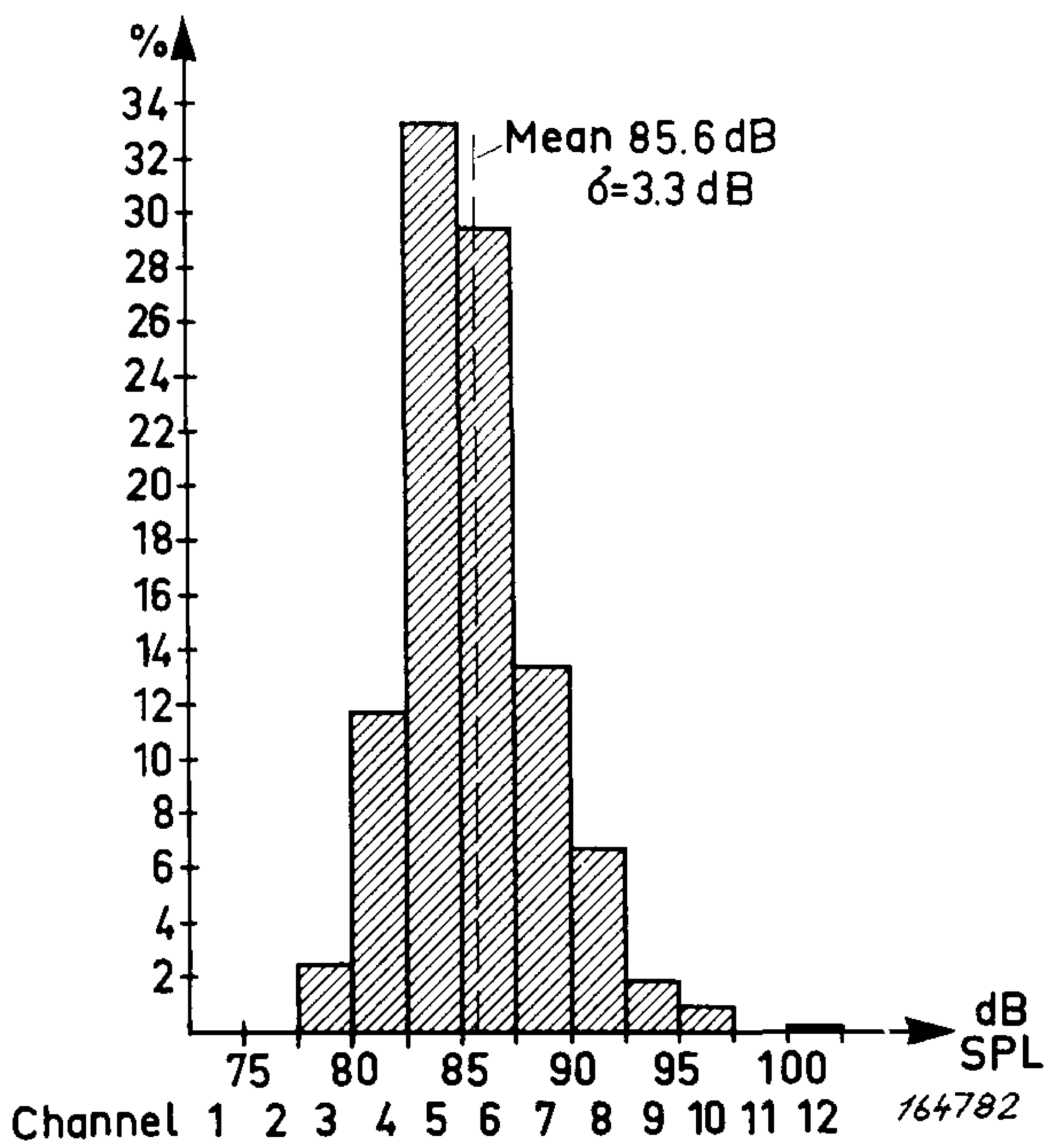
From average frequency spectra obtained during the measurements it is possible to estimate the corresponding DIN-phon values, and the distribution obtained in this way is shown in Fig. 12b.

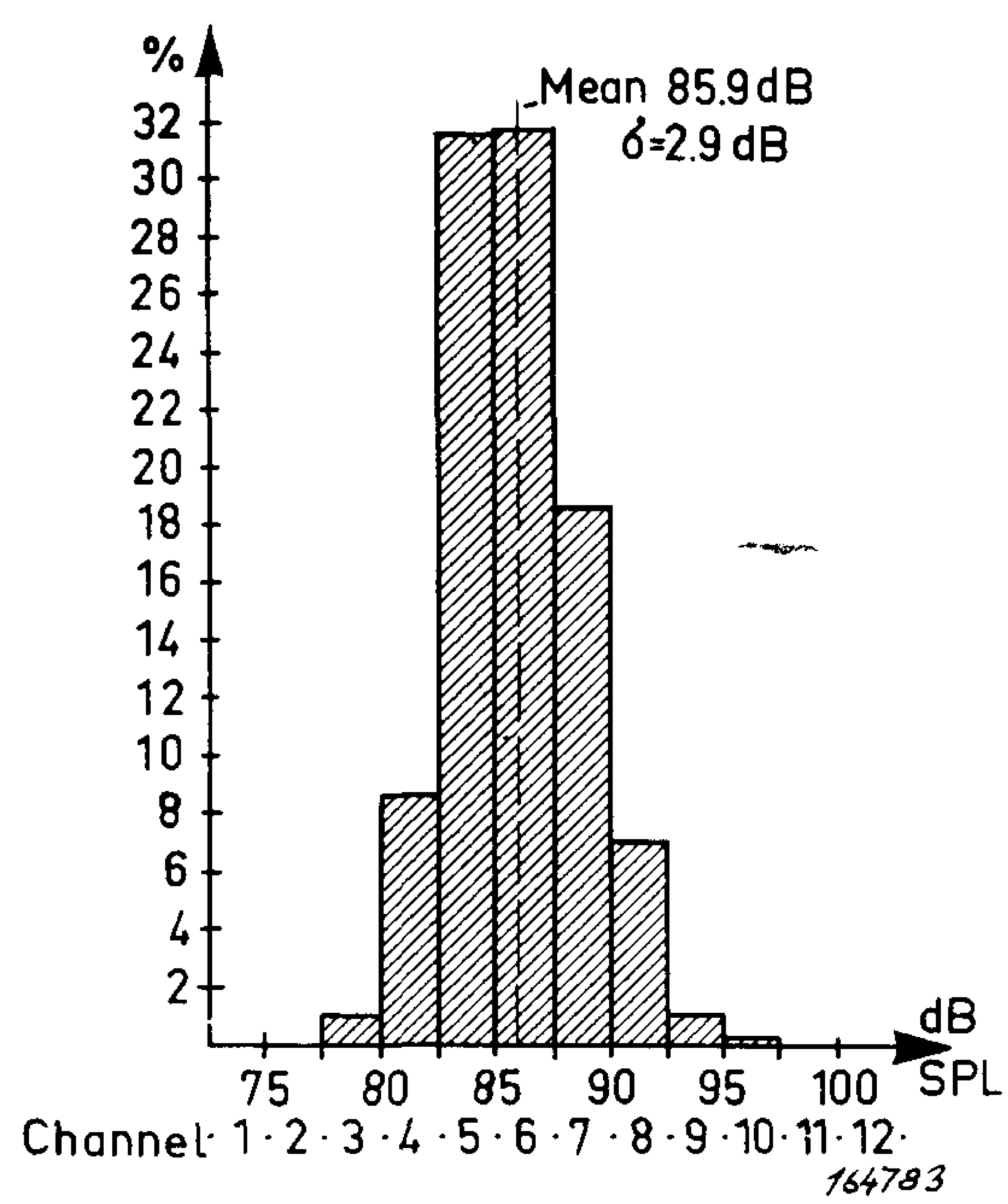
From Fig. 12b it can be seen, that the mean noise level nowadays seems to have increased further in relation to the mean noise level measured in Düsseldorf 1952, and that the noise level 77.8—82.8 DIN-phon takes place 60 % of the sampling time. On the other hand, it is not quite correct to compare the results from these measurements, when the measuring condition and the measuring places are not the same, but it gives a good idea of the steadily increasing traffic noise level.

The noise level of 85—87.5 dB of the curves in Fig. 13 takes place between 31 % and 37 % of the sampling time, while the noise level of 85—90 dB of the curve in Fig. 12a takes place 60 % of the sampling time. This looks a little confusing, but the reason is that the interval ranges and sampling time in the two cases are different. In Fig. 12a a channel unit is equal to 5 dB while in Fig. 13 it is only 2.5 dB, and the sampling times are respectively 100 min. and 15 min.









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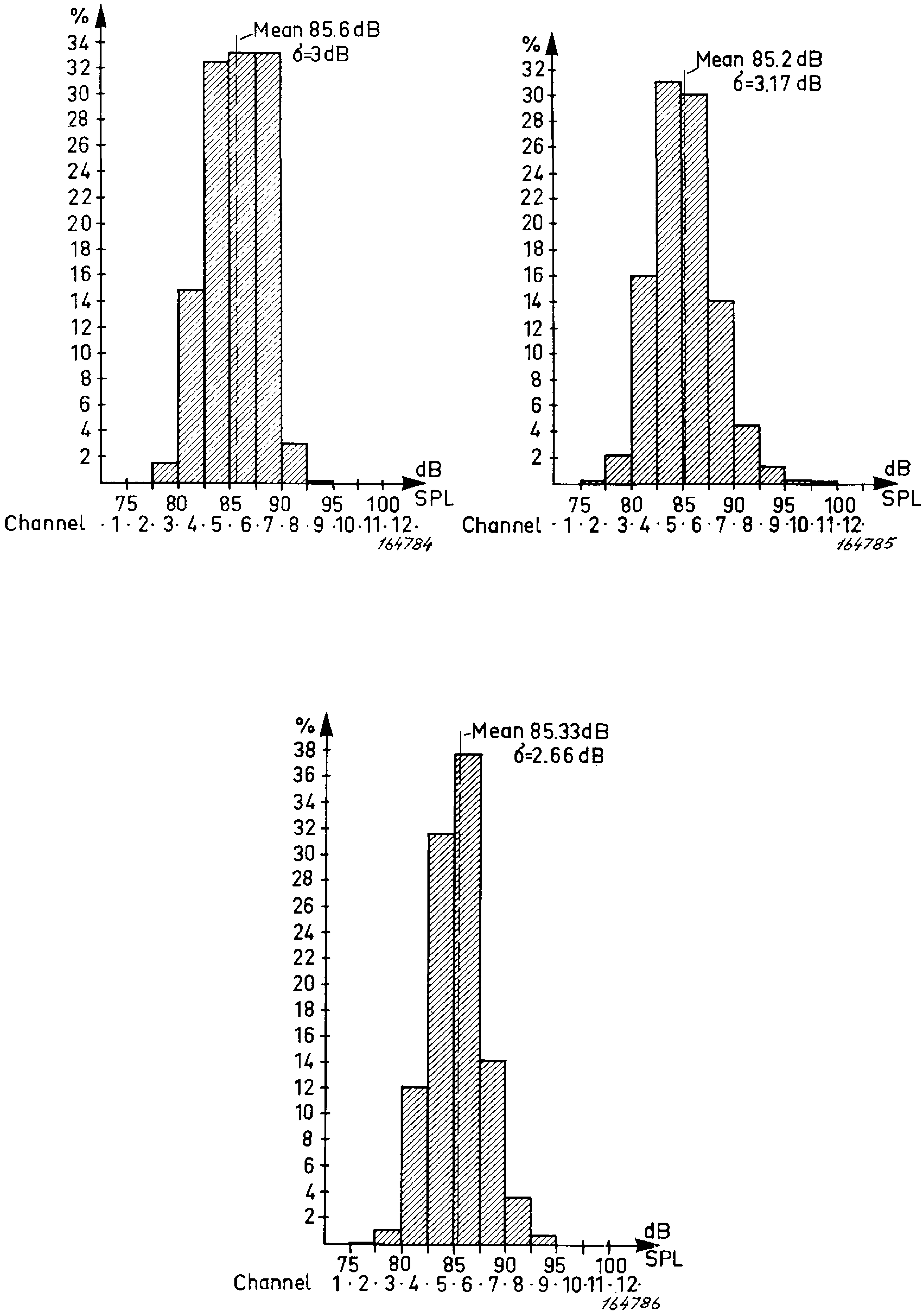

Fig. 13. Seven histograms obtained from 2.15 p.m. to 4.15 p.m. The sampling time for each curve is 15 min.

If the sampling time is increased, when measurements on traffic noise are made, one may find that the standard deviation is increasing. This can be explained by the noise level variations during the day and the night.
During the measurement of traffic noise it was noted, that only the heavy trucks, buses and trams caused the very high noise levels, and it should therefore be possible to determine the proportion of the time that the higher noise levels will exist, if a selective traffic count is made. This method may then be used for a rough estimate when statistical measuring instruments such as Type 4420 are not at hand.
In city planning great care is taken to reduce the noise level of the traffic and industry in the residential areas, and it will be very useful to employ the Statistical Distribution Analyzer for examination of the noise level in these areas.
Another application of the Statistical Distribution Analyzer which may be of value in traffic investigations is as follows. If the phenomena being investigated follow no particular time sequence, it is possible to synchronize the triggering pulses with the events. This condition is obtained, if the period selector on the Statistical Distribution Analyzer is switched to the "Ext." position, and the synchronizing signal is connected to the "Ext. Gen." pin of the remote-control socket at the rear of the instrument.

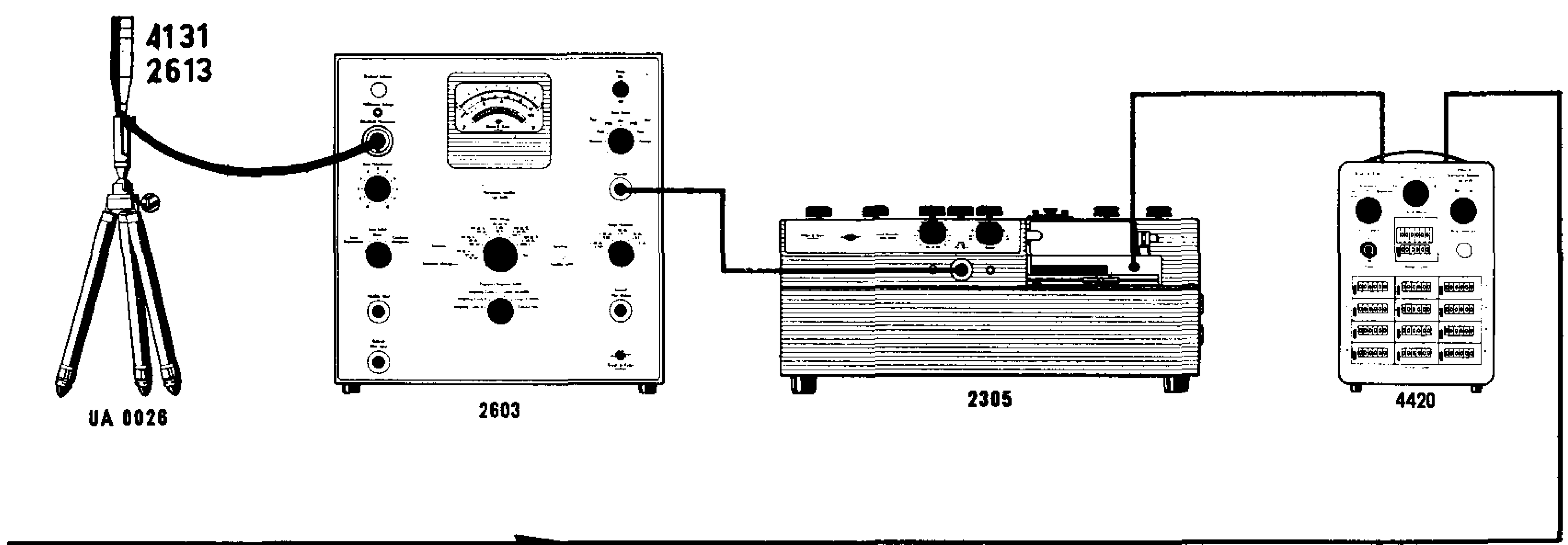

Fig. 14. Measuring arrangement for special statistical distribution analysis.

The measuring set-up shown in Fig. 14 will give the statistical distribution of noise level with respect to the events, (for example number of cars), and a histogram is shown in Fig. 15.
The synchronizing signal should be such that the "Ext. Gen." pin of the Statistical Distribution Analyzer is either shorted to ground or given a negative-going pulse, whereby the total register and the counter for which contact is made will register one digit.

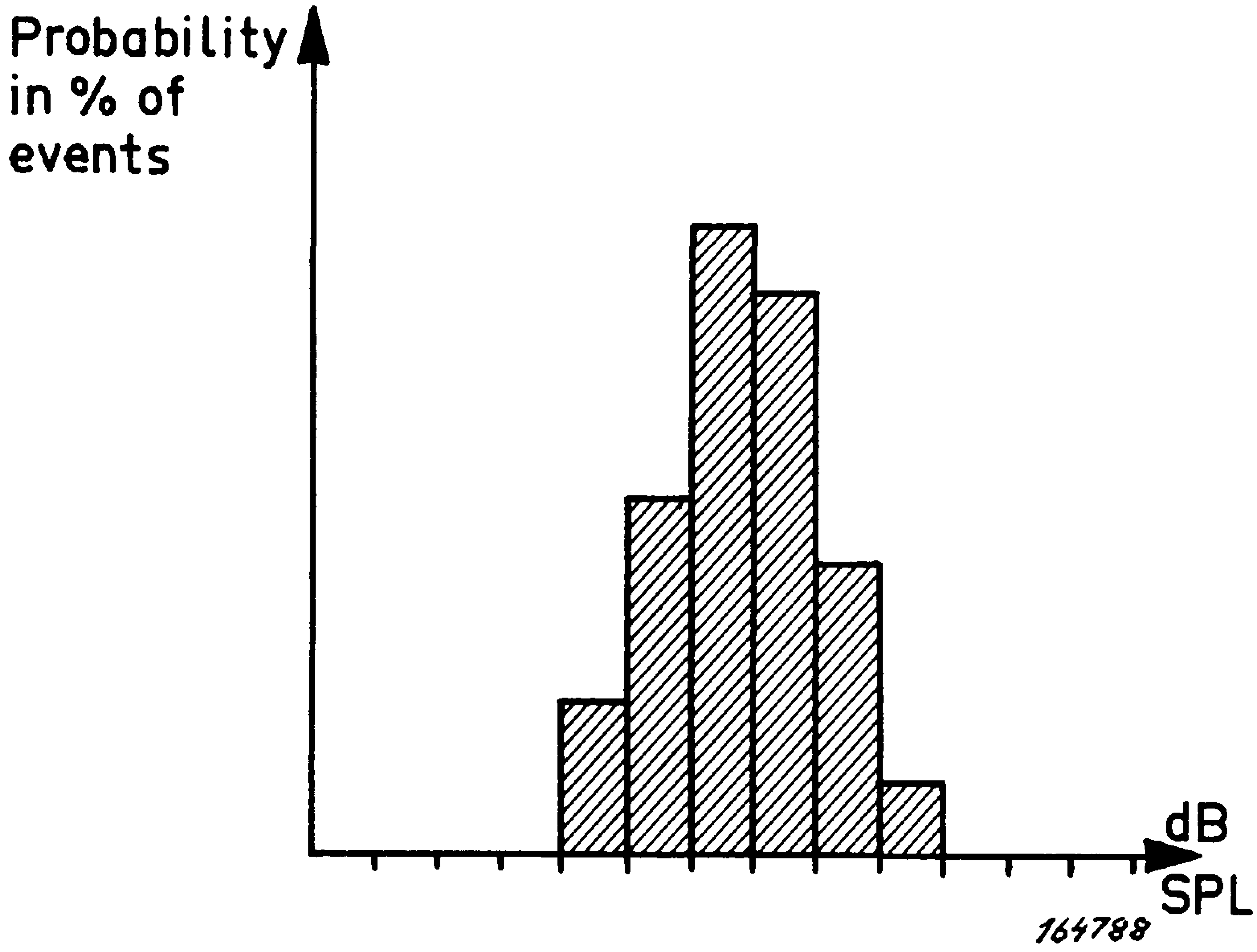

Fig. 15. Histogram of the probability of events.

Airport Noise.

The noise in the vicinity of airports is increasing steadily year by year. The jet aeroplane is firmly established as a means of transport and the super or hypersonic liners are in the design stages. This means that the noise from airports is going to continue increasing for a long time yet, because silencing of the jet engines results in decreased performance and is therefore not always practicable.

A lot of effort has been spent on determining how to evaluate the noisiness due to aircraft. See for example Kryter, "Scaling Human Reactions to the Sound from Aircraft", JASA 31 p. 1415, 1959 or Kryter and Pearsons, "Judgement Tests of the Sound from Piston, Turbojet and Turbofan Aircraft", Sound, Vol. 1, No. 2, 1962. These investigators have attempted to determine a procedure whereby the "unwantedness" of complex sounds can be measured or calculated from relatively simple measurements of amplitude-frequency spectra. Kryter's "Perceived Noise Level" (PNdB) is now commonly used in airport noise evaluations.

To determine the annoyance caused by air traffic to people living in the vicinity of airports it is not enough to calculate the perceived noise level for a single aircraft. It is also necessary to know how often or for what percentage of time such a level is reached. Fifty aircraft a day would

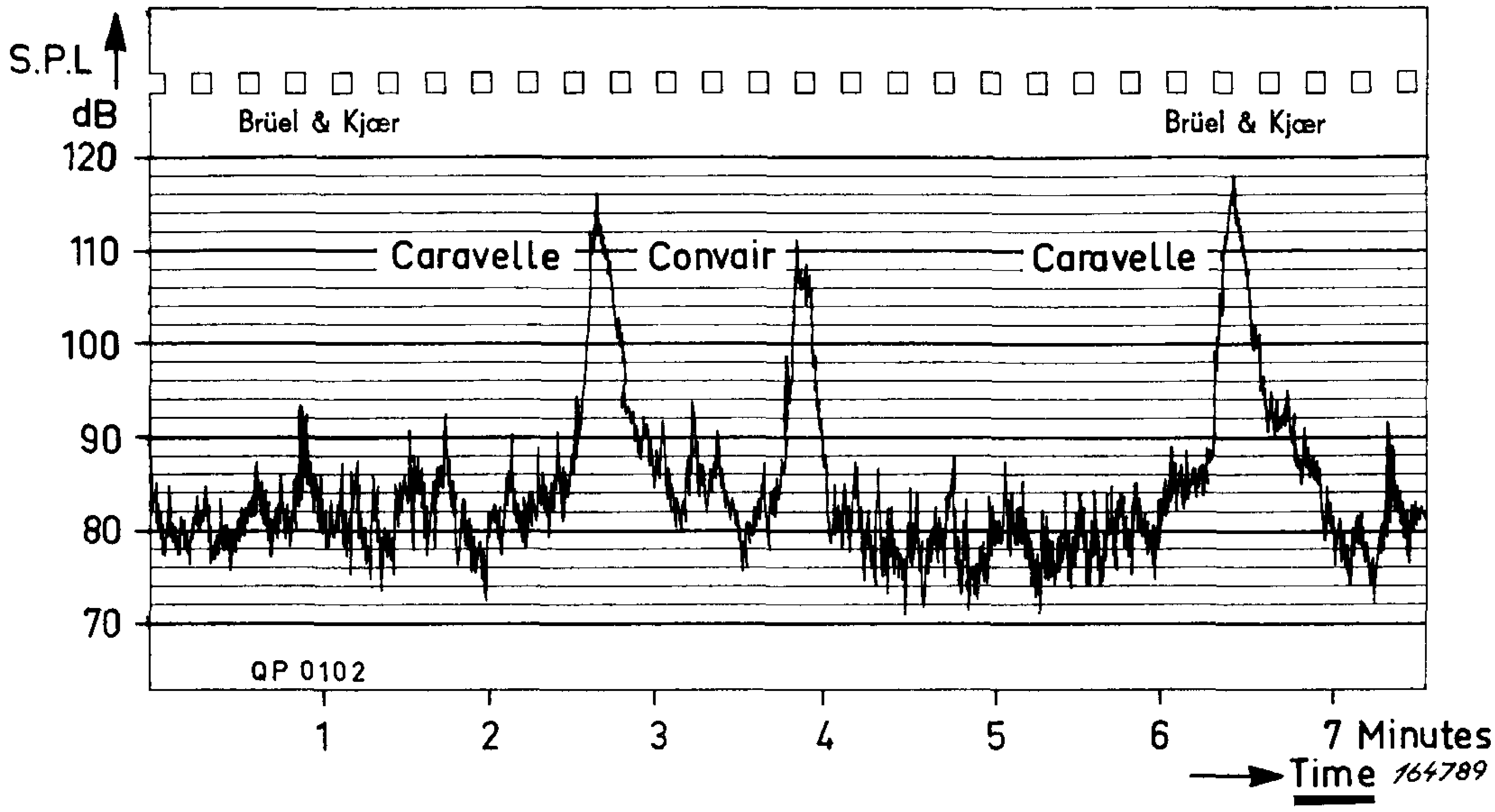

Fig. 16. Overall sound pressure level measured at Copenhagen airport.

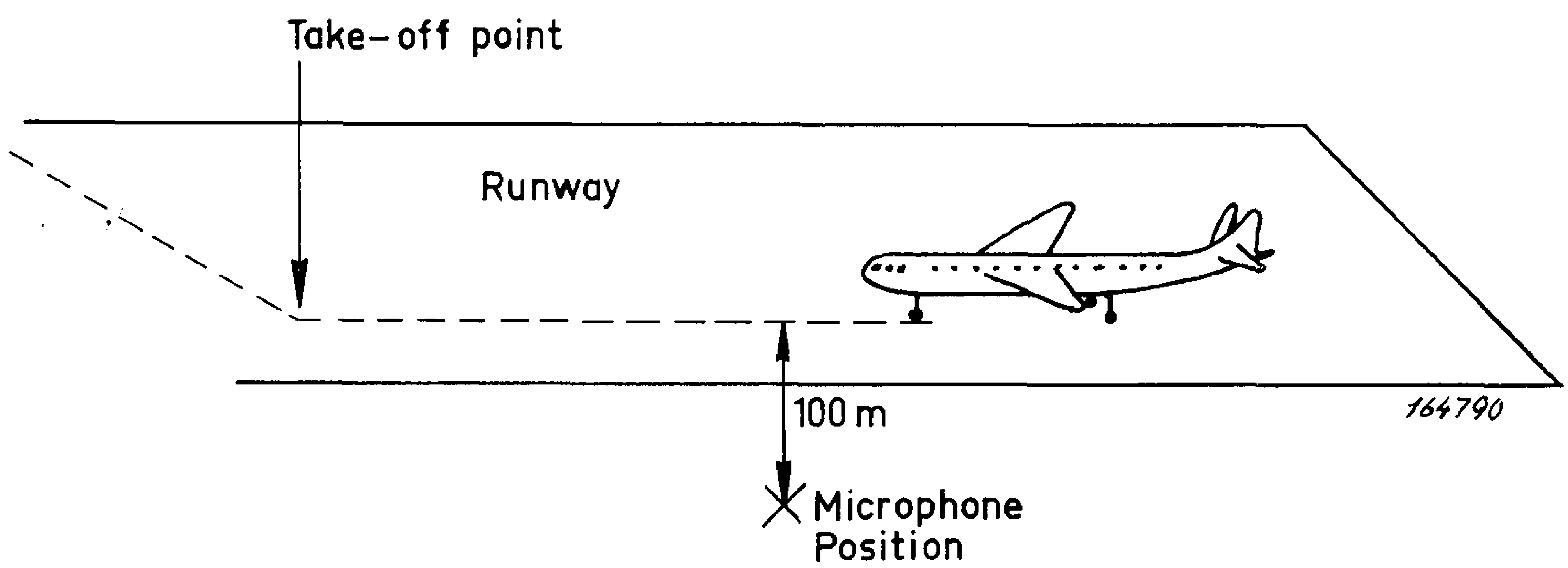

Fig. 17. Microphone position in relation to runway.

certainly be more annoying than five, and fifty aircraft during the night would be much more annoying than the same fifty during the day.
The Statistical Distribution Analyzer might be used to give information about this aspect of the noise. In the following example the noise near an airport runway was investigated, using a microphone amplifier with a linear frequency characteristic, but the same kind of investigation could be done with a weighting network. Values of PNdB are usually calculated from measurements of octave band sound pressure levels, but a weighting network characteristic has been suggested for giving the values directly.*)
This weighting network is however not in common use.

*) When this weighting network is used for evaluating noisiness, the values should be given in "dBN" in order to show that they are not calculated from octave band sound pressure levels.

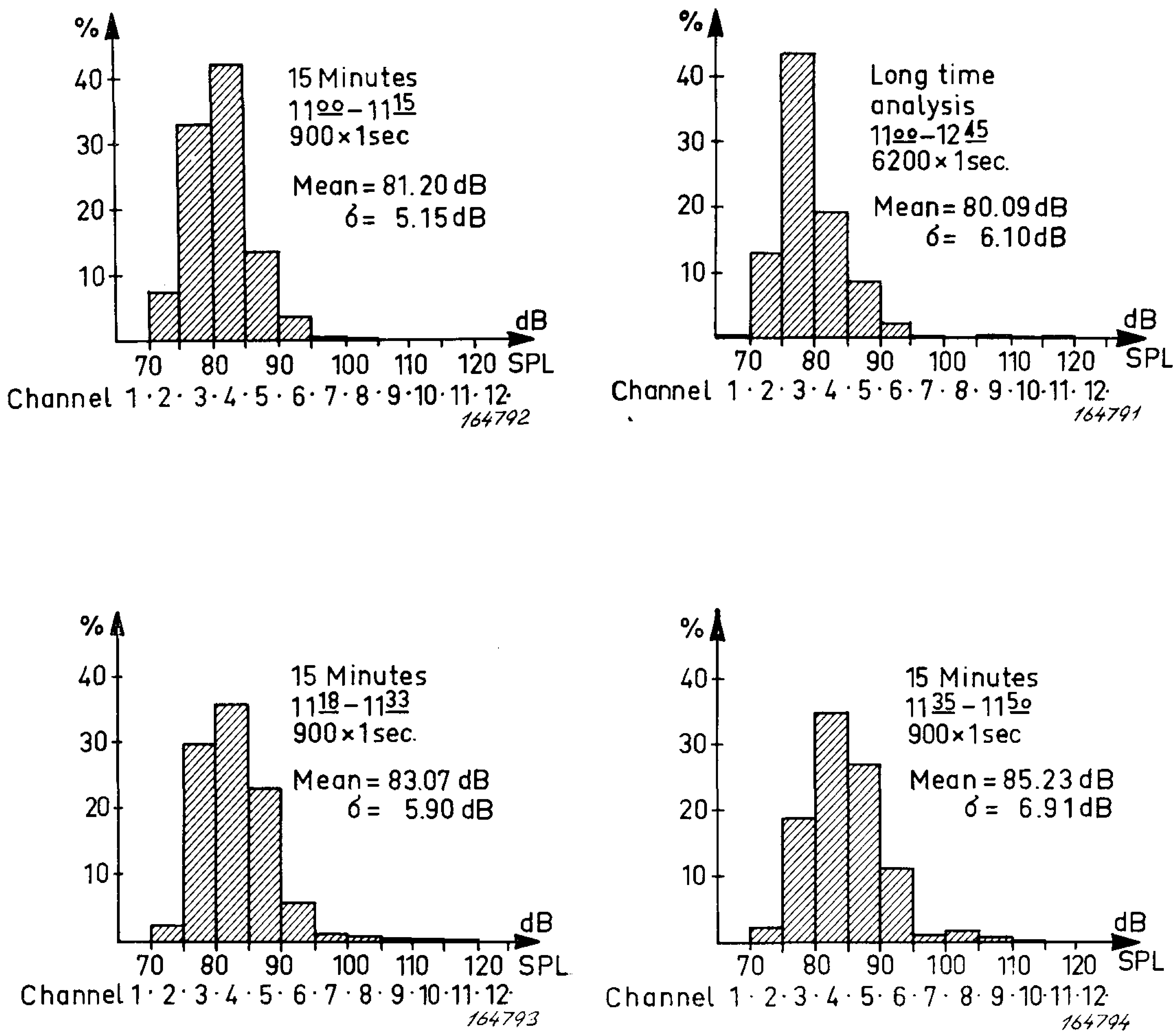

Fig. 18. Statistical Distribution of sound pressure level near a runway at the Copenhagen International Airport.

The chart shown in Fig. 16 was obtained during a two hour visit to the Copenhagen International Airport. It represents the overall sound pressure level for some 7 minutes at a position 100 m (300 ft.) from a runway as shown in Fig. 17.

Two identical set-ups similar to the one shown in Fig. 11 were used in order to get the statistical distribution of the sound pressure level at this position. One set-up was running continuously for 6200 sec. with pulse repetition period 1 sec., while the other set-up was running for 15 minutes at a time with the same repetition period. The results obtained are shown graphically in Fig. 18.

It can be seen from the results given in Fig. 16 and 18 that the noise in this case is not purely random in character. The background noise which is composed of the noise from cars, small airplanes and large airplanes landing, is random and approximately Gaussian in distribution, but on this is superposed the high peaks (up to 120 dB) resulting from large planes taking off. It is therefore not so useful to quote a mean sound pressure level for this type of noise, as it would tend to disregard the high peaks which are definitely the most annoying or damaging to the hearing mechanism. The information can, however, be used in the form given by the Statistical Distribution Analyzer, showing for example the percentage of time for which the sound pressure level lies between 100 and 105 dB. The information can then be used for determination of possible hearing loss or other effects suffered by people working or living near an airfield.

In view of the interest in determining the statistical distribution of sound levels and of their possible danger to hearing and good health, it is obvious that this type of analysis, which can quickly and effectively measure if dangerous limits are exceeded or not, and for what length of time particular levels are exceeded, will be of great value in future noise investigations.

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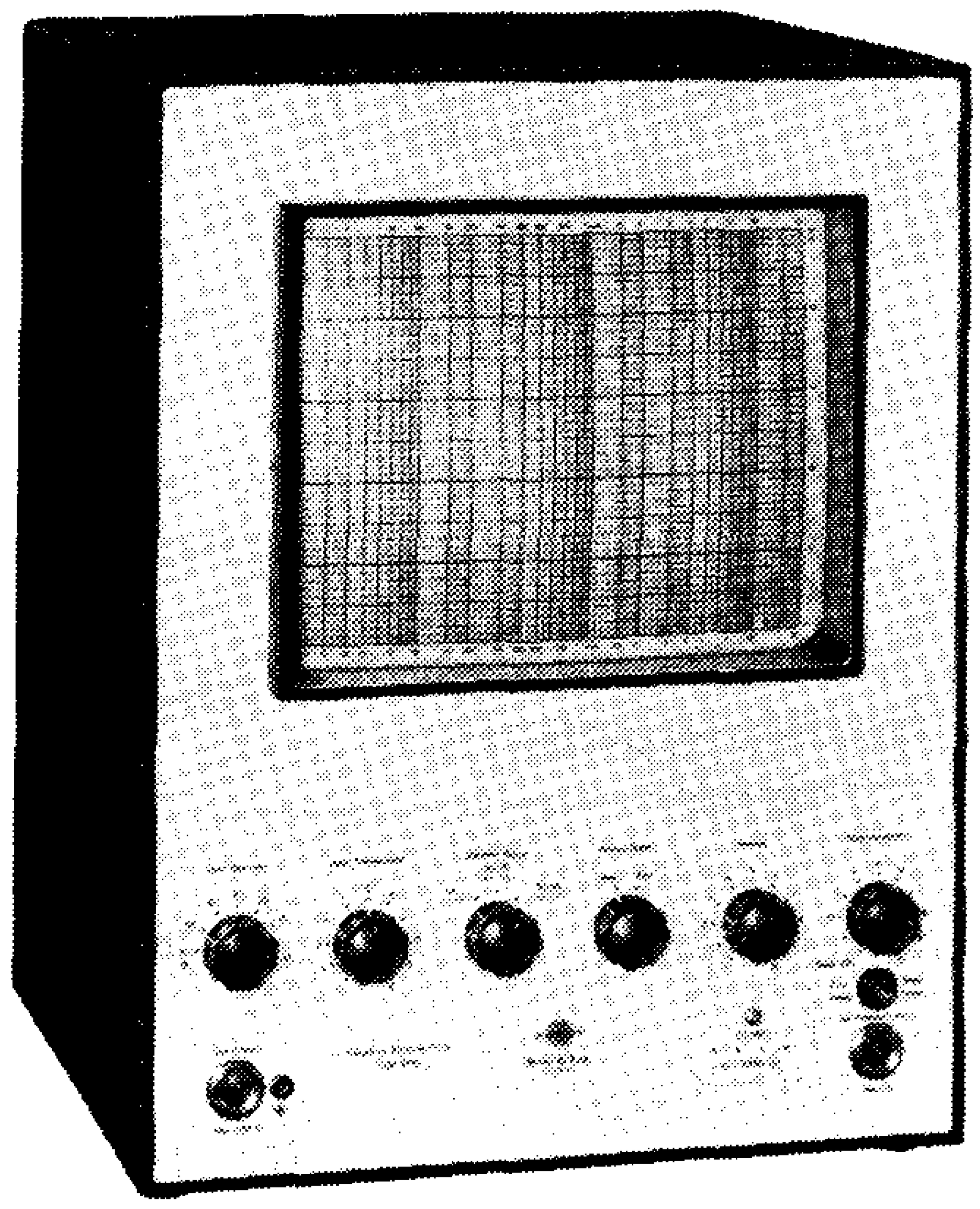
News from the Factory

Frequency Response Tracer Type 4709.

The release has just been announced of the new Frequency Response Tracer Type 4709. This is a completely new design, incorporating some of the features of the previous model, Type 4707, but entirely new principles have been included, making the instrument much more versatile and extending its field of application considerably.



The Frequency Response Tracer, as the name implies, gives the frequency response of a test object on the screen of a 14″, long persistence, cathode ray tube. It may be used in the production control of microphones, loudspeakers, earphones, tape-recorders, audio-frequency filters and other electro-acoustic devices in the frequency range 20—20000 c/s. Calibrated scales are supplied for the screen with the horizontal direction graduated in logarithmic frequency and the vertical direction in dB or linear volts. Interchangeable external plug-in units are supplied, giving the instrument the frequency ranges 20—20000 c/s or 200—5000 c/s.

The x- and y-deflection of the cathode ray tube are both controlled by the input signal so that the instrument may also be used for checking the frequency response of long telephone and radio communication lines.

An external frequency generator is used as a signal source, and the Frequency Response Tracer is equipped with the control circuits necessary for automatic operation of a sweep motor which may be installed in a beat frequency oscillator such as the B & K Type 1022. Automatic scanning of any predetermined frequency range can thus be obtained, which is very convenient in production line tests. Sweep speeds range from about 1/3 octave per second to 3 octaves per second.

The large screen makes the Frequency Response Tracer easy to read, and the great versatility in application makes this instrument very attractive both for production line and laboratory purposes.

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