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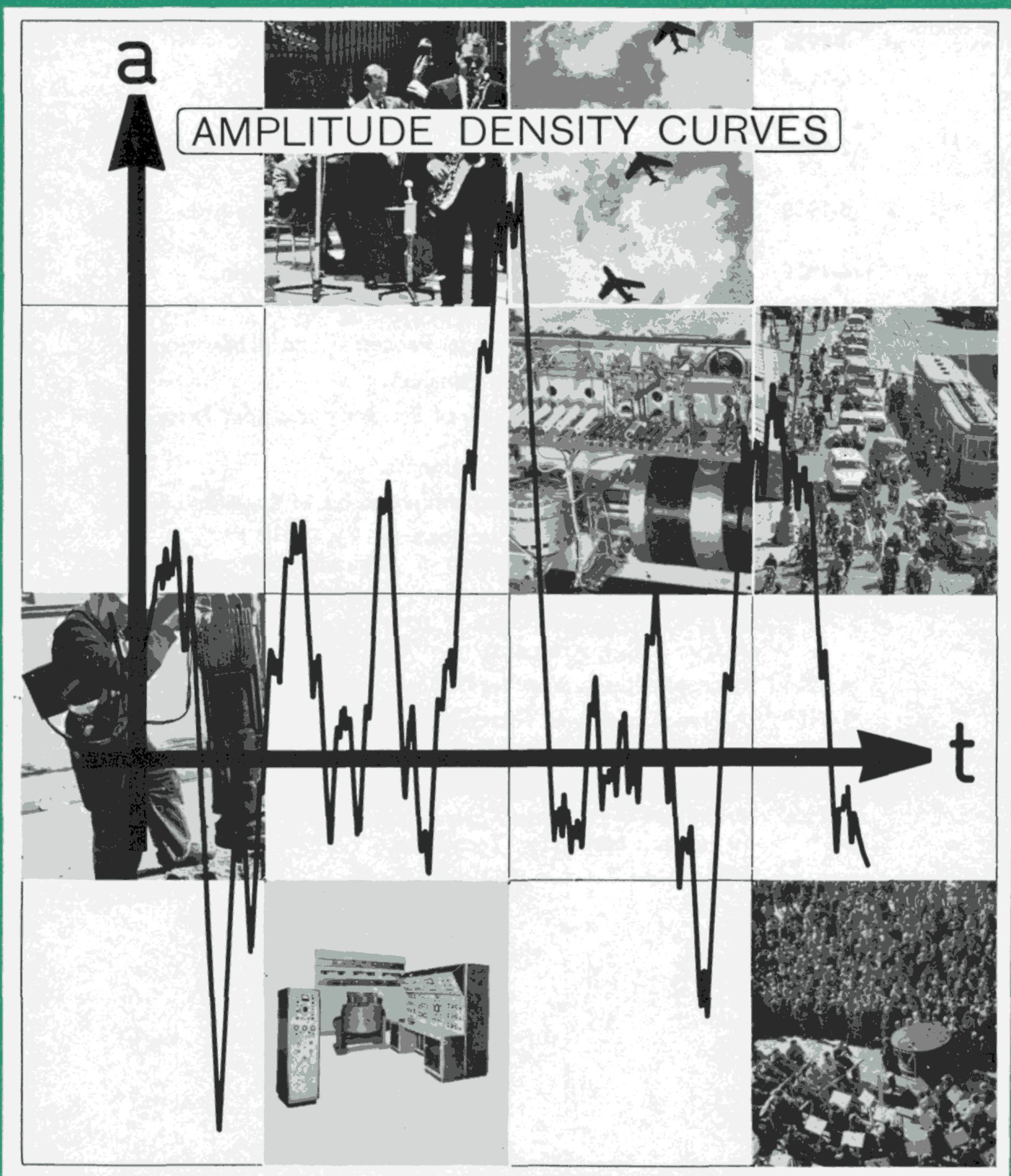

No. 4

1959

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CONTENT

DET BERLINGSKE BOGTRYKKERI

Automatic Recording of Amplitude Density Curves

by

Jens T. Broch, Dipl. Ing. E. T. H.

SUMMARY

After introducing the concept of amplitude density the similarity between the A.A.-value and the "arithmetic average deviation" as well as the R.M.S. value and the "standard deviation" is shown. A measuring system consisting of a Level Recorder Type 2304, an Inverter Type 4610, an oscilloscope, and a photomultiplier unit is then described, by means of which the amplitude density curve can be plotted automatically. The advantages of logarithmic amplitude density recording are briefly outlined, and some examples of the use of the equipment given. By adding a Spectrometer Type 2110 complex signals can be analyzed. Furthermore, amplitude density curves, one for each Spectrometer filter, can be recorded automatically. The Spectrometer also directly indicates the "standard deviation" and the "arithmetic average diviation".
Finally the calibration and limitation of the equipment are discussed.

RÉSUMÉ

Après avoir introduit la notion de densité d'amplitude, on montre la similitude entre la « valeur moyenne arithmétique » et la « déviation moyenne arithmétique », anisi qu'entre la valeur efficace et la « déviation standard ».
On décrit alors un système de mesure constitué d'un Enregistreur de Niveau Type 2304, d'un Inverseur Type 4610, d'un oscilloscope, d'un photomultiplicatrice, grâce auquel on peut enregistrer automatiquement la courbe de densité d'amplitude. On fait ressortir brièvement les avantages d'un enregistrement logarithmique de la densité d'amplitude et l'on donne quelques exemples d'emploi de l'équipement. Des signaux complexes peuvent être analysés grâce â l'adjonction d'un Spectromètre Type 2110. En outre il est possible d'enregistrer automatiquement une courbe de densité d'amplitude pour chaque filtre du Spectromètre. Cet appareil indique également directement la « déviation standard » et la « déviation moyenne arithmétique ».
On étudie enfin l'étalonnage et les limitations d'emploi de l'équipement.

ZUSAMMENFASSUNG

Das Signal, dessen Häufigkeitskurve registriert werden soll, wird auf das Y-Plattenpaar eines Oszilloskops geführt, vor dessen Schirm eine Schlitzblende parallel zur X-Richtung mit gleichmässig langsamer Geschwindigkeit vorbeiwandert. Das durch den Schlitz fallende Licht entspricht dem Amplitudendifferential, es wird von einem photoelektrischen Sekundärvervielfacher aufgefangen und als Gleichspannung der Registriereinrichtung, bestehend aus Pegelschreiber 2304 und Zer-

hacker 4610, zugeführt. Vorteilhaft erscheint die Verwendung eines logarithmischen Registrierpotentiometers, welches die Gaussche Häufigkeitskurve in eine bequemer auswertbare Parabel verwandelt.
Schaltet man vor die Messeinrichtung einen selektiven Verstärker, z.B. Terzfilter-Analysator 2111, so kann man die Häufigkeitskurven der verschiedenen Anteile eines NF-Spektrogramms registrieren. Die »normale Abweichung« und die »Arithmetische Mittelwertsabweichung« kann man unmittelbar am Anzeigeinstrument des Terzfilter-Analysators ablesen.
Die Einleitung des Artikels behandelt die Begriffe »Amplitudenhäufigkeitsdichte«, »Arithmetische Mittelwertsabweichung«, »Effektivwert« und »normale Abweichung«, eine Betrachtung über Eichmöglichkeit und Messgenauigkeit der Registriereinrichtung bildet den Schluss.

A stationary periodic signal, such as a sine wave, is completely described by means of three quantities, the amplitude, the frequency and the phase.
However, a great number of processes occuring in nature give rise to signals which are quasi stationary but not periodic. Typical examples are rocket engine noise, noise from certain types of machines (for example from typewriters), crowd noises, music played by an orchestra, electrical resistor noise, tube noise, and signals derived from aerodynamic turbulence, traffic counters etc.
Since the amplitude values of these types of signals are not periodic, it has been found convenient to introduce the concept of *amplitude density* instead of amplitude, because the different possible amplitude values occur with a certain "density" when the phenomenon is studied over a certain period of time. The concept of amplitude density corresponds to the concept of probability density in statistics.
To give a meaning to the word density it is obviously necessary to divide the amplitude scale into small divisions Δx and define a measure for amplitude

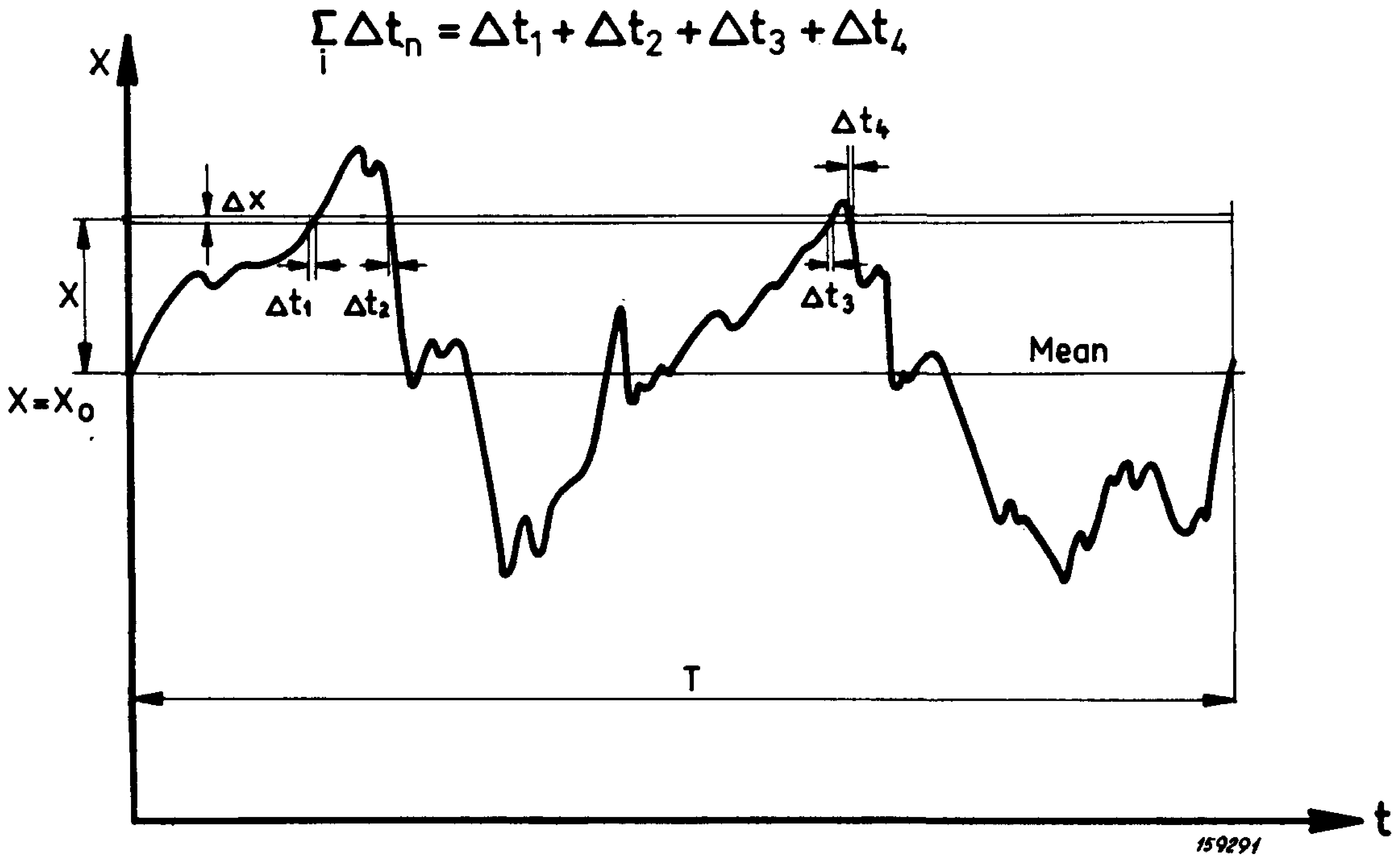

Fig. 1. Time record of a random process.

values to be found within Δx. The latter can be done by measuring how long the signal being investigated has amplitude values between x and $x + \Delta x$ relative to the total length of time over which the phenomenon is being studied (see also Fig. 1):

$$\text{Amplitude probability:} \quad P(x, x + \Delta x) = \frac{\sum_i \Delta t_n}{T} \qquad \text{(a)}$$

The amplitude density is thus:

$$p(x) = \lim_{\Delta x \to 0} \frac{P(x, x + \Delta x)}{\Delta x} \qquad \text{(b)}$$

By varying the value of x from $-\infty$ to $+\infty$ and plotting $p(x)$ as a function of x the amplitude density curve for the signal in question is found.

The shape of this curve can vary considerably, the most well known amplitude density curve being that obtained from a normal (Gaussian) random process. This process is an analytical (continuous) process, and the normalized*) amplitude density curve is given by:

$$p(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x - x_0)^2}{2\sigma^2}}$$

σ = standard deviation (r. m. s. — value)

x_0 = mean value (see also Fig. 1)

The above formula can be derived in several ways, both by solving the differential equations used in theoretical physics to describe certain processes and from

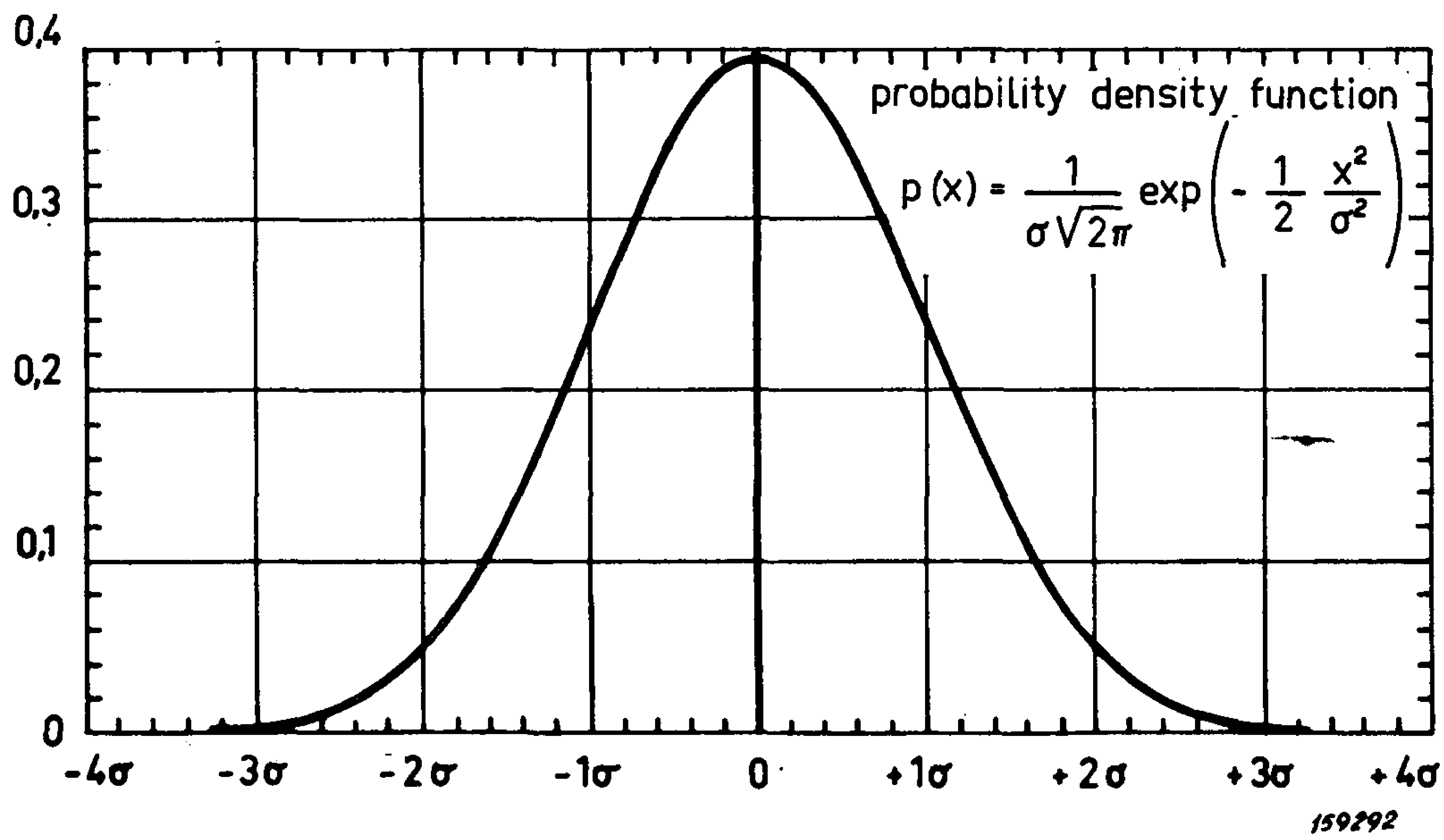

Fig. 2. The normalized Gaussian amplitude density curve.

*) Normalized: $\int_{-\infty}^{+\infty} p(x)\,dx = 1$ where p(x) is the amplitude density.

a purely statistical point of view when an infinite number of independent events are combined.

From the Gaussian curve a number of interesting characteristics can be deduced:

1. The two parameters σ and x_0 characterize this curve in a manner similar to the way the constants a and b characterize the straight line $f(x) = ax + b$.

2. If $x_0 = 0$ the curve is centered around zero as a mean, see Fig. 2.

3. The arithmetic average deviation from the mean is:

$$x_{a.a.} = \int_{-\infty}^{+\infty} |x| \cdot p(x)\,dx$$

4. The standard deviation (r.m.s. deviation) from the mean is:

$$\sigma = \sqrt{\int_{-\infty}^{+\infty} x^2\, p(x)\,dx}$$

The expressions given under 3 and 4 are equivalent to those also used to characterize the amplitude of *periodic* signals. The equivalence of the expression given under 3 and 4 for periodic and random signals will be clear from the following:

If the phenomenon is studied over a certain period of time, T, then the probability of finding amplitude values between x and $x + \Delta x$ is according to (a) and (b) (see also Fig. 1):

$$P(x, x + \Delta x) = \int_{x}^{x + \Delta x} p(x)\,dx = \frac{\sum_i \Delta t_n}{T} = \frac{\Delta t}{T}$$

where $p(x)$ is the amplitude density, and $\Delta t = \sum_i \Delta t_n$

The arithmetic average deviation is given by:

$$X_{a.a.} = \int_{-\infty}^{+\infty} |x| \cdot p(x)dx = \lim_{\Delta x \to 0} \sum_{-\infty}^{+\infty} |x| \cdot P(x, x + \Delta x)$$

$$= \lim_{\Delta t \to 0} \sum_{0}^{T} |x| \cdot \frac{\Delta t}{T} = \frac{1}{T} \int_{0}^{T} |x|\,dt$$

which is the well-known expression for the arithmetic average value of a periodic signal.

Similarly the expression for the standard deviation can be shown to be equivalent to

$$X_{r.m.s.} = \sqrt{\frac{1}{T}\int_0^T x^2\, dt}$$

Returning to the concept of amplitude density it can be seen that if Δx in (b) is chosen to be small the probability of finding amplitude values between x and $x + \Delta x$ is approximately:

$$P(x, x + \Delta x) \simeq p(x) \Delta x$$

By measuring $P(x, x + \Delta x)$ and plotting the result, the amplitude density curve of the process will be obtained to a first approximation.
Lately several instrumentation systems have been developed by means of which the amplitude density curve can be obtained, either directly, or through measurements of the probability distribution. Most of these are systems based on electronic gating circuitry and are more or less complicated and expensive. One, which has been developed by Bolt, Beranek and Newman Inc., in the U. S. A. has, however, the unique feature that the curves obtained are self normalized. In the following a relatively inexpensive system which is less refined but have several advantages with respect to simplicity and method of representing the amplitude density curve will be described. Some experimental results obtained by applying the instrumentation to practical problems are also given.
To make use of this system the data to be studied must be available in the form of an electrical signal which can be displayed on the screen of a cathode ray oscilloscope. This need not, however, be considered a serious limitation because most physical phenomena can be transformed into electrical signals by means of suitable transducers.

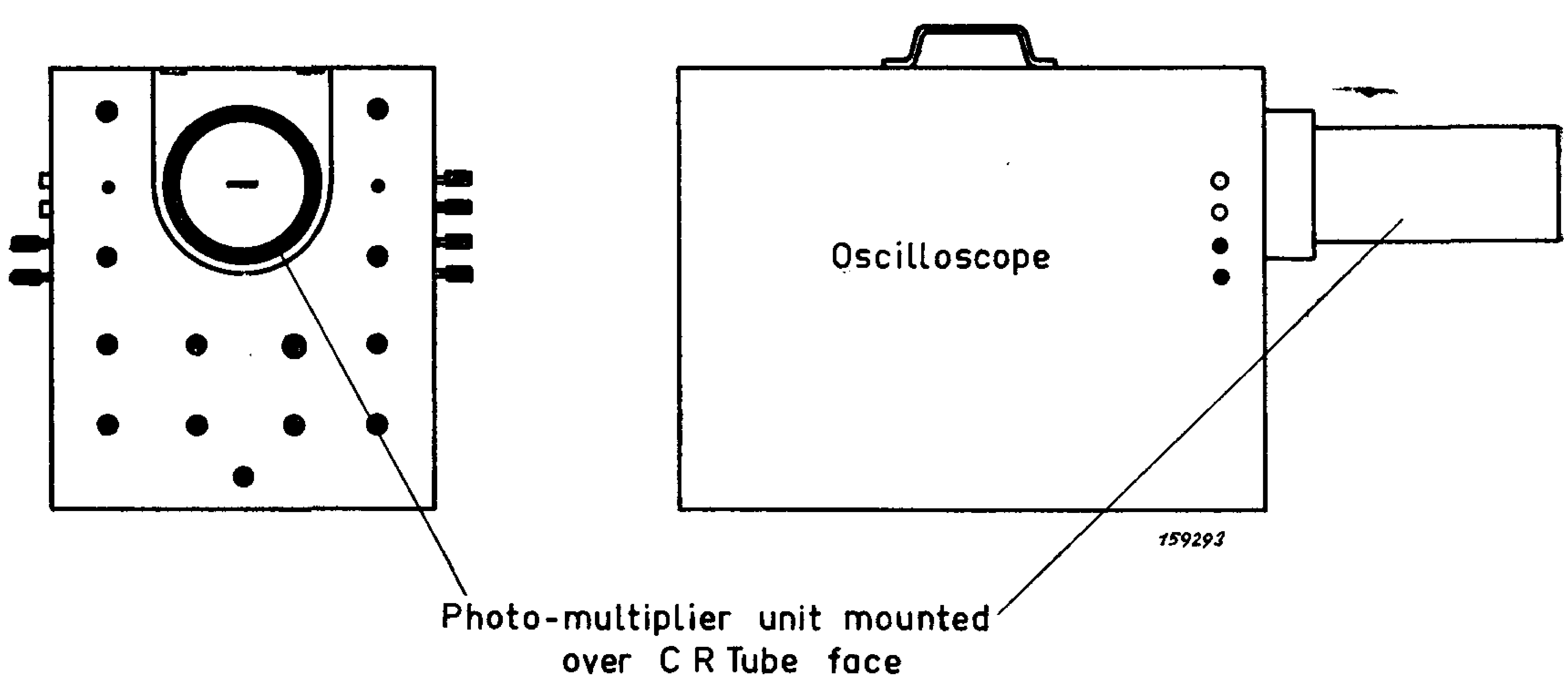

Fig. 3. Cathode ray oscilloscope with the photomultiplier unit mounted.

The light intensity in a differential area of the oscilloscope screen will, when the electrical signal is applied to the Y-axis of the oscilloscope and a suitable sweep speed is chosen for the X-axis, be proportional to the length of time that the electron beam is within this area. The accuracy of this statement will depend to a certain extent upon the afterglow of the cathode ray tube, and this should, consequently, be chosen as short as possible.
The light intensity is measured by means of a photomultiplier tube with a narrow slit opening mounted horizontally across the centre. The instrumentation described is shown in Figs. 3 and 4. The sweep rate of the oscilloscope together with the slit length L determines the sampling time T of the different (continuously varying) samples.

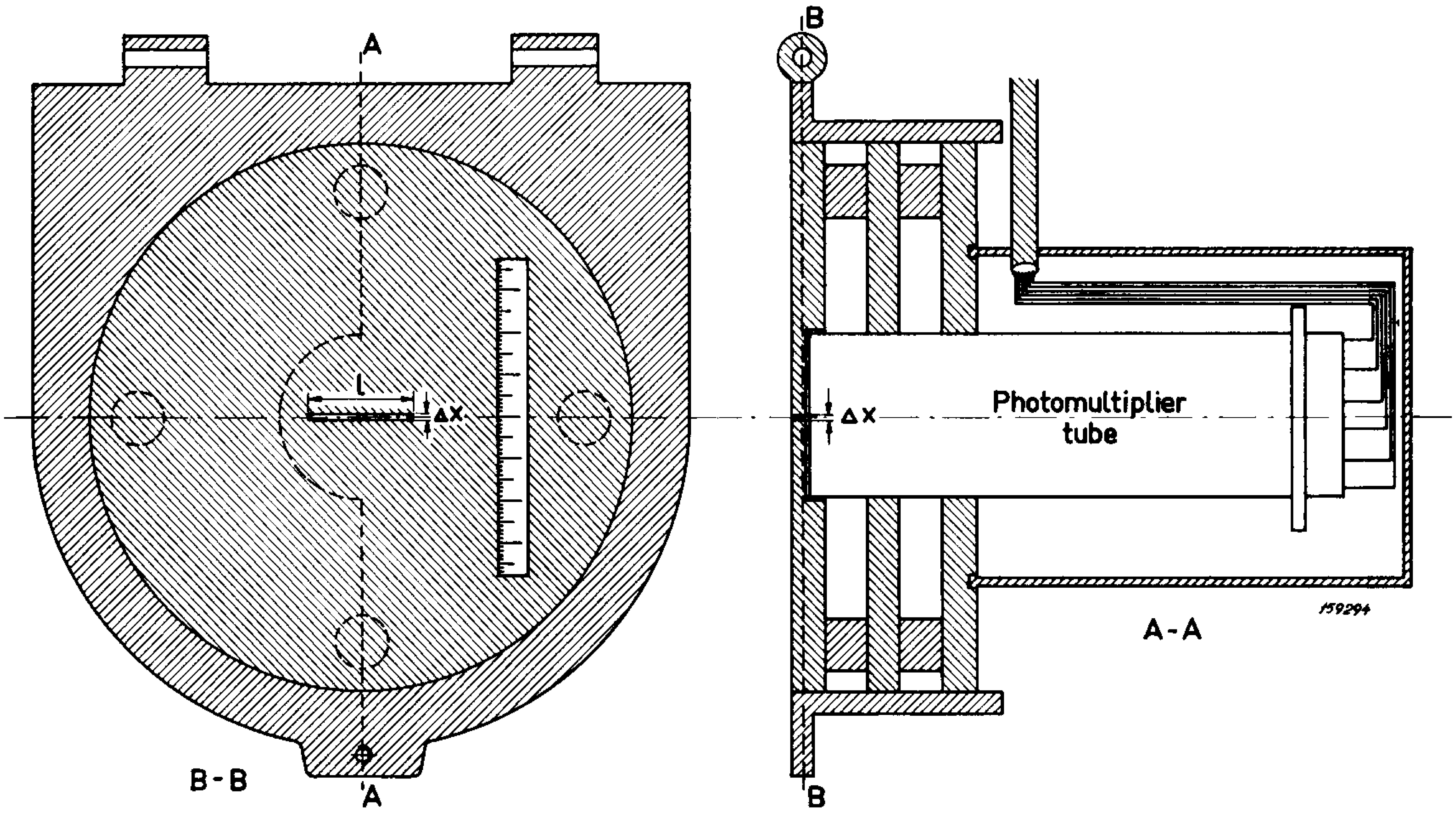

Fig. 4. Sectional views of the photomultiplier unit.

To move the slit relative to the signal amplitude it is only necessary to displace the X-axis of the oscilloscope in the Y-direction, keeping the slit fixed in the centre line of the oscilloscope screen.
By moving the X-axis by hand and measuring the current in the photomultiplier tube for each position of the X-axis the amplitude density curve of the signal on the oscilloscope screen can be measured manually. This method is, however, extremely timeconsuming when a great number of curves have to be measured. A much more refined technique for the handling of large quantities of statistical material such as vibration data from guided missiles or high speed aircraft, etc. is obtained by using a logarithmic level recorder and the convertion of the slowly varying d. c. output from the photomultiplier into a. c. by means of a suitable d. c. — a. c. inverter. If the potentiometer of the oscilloscope used for displacing the X-axis in the Y-direction (Y-position potentiometer) is driven

from the motor in the level recorder the required amplitude density curve can be recorded automatically to a logarithmic scale.
Fig. 5 shows such an arrangement utilizing the B & K High Speed Level Recorder Type 2304 and Inverter Type 4610.

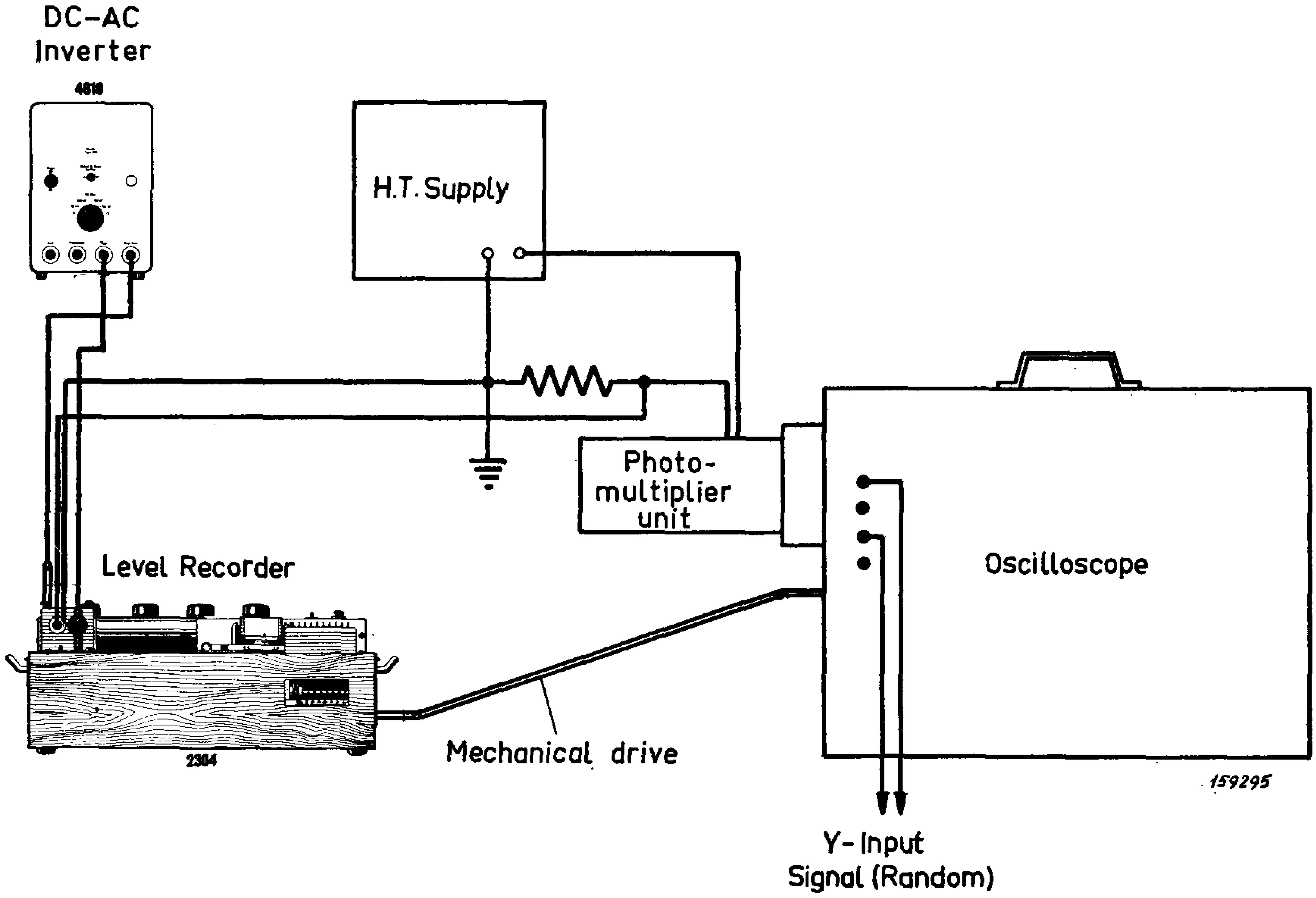

Fig. 5. Measuring arrangements for the automatic recording of amplitude density curves.

The only modification necessary to the commercially available instruments used in the arrangement shown in Fig. 5 to enable complete automatic operation of the equipment is to change the Y-shift potentiometer on the oscilloscope. The potentiometers used normally on cathode ray oscilloscopes have two mechanical stops which prevent the potentiometer slider from turning a full 360°. These stops should be removed and resistors of suitable values be connected as shown in Fig. 6. This measure is necessary for continuous rotation of the potentiometer slider in one direction. The resistors ensure an unbalance in the potentiometer circuit, even when the slider is moving from full resistance to zero, before a new sweep is started on the oscilloscope screen.
It was mentioned above that the level recorder should be of the logarithmic type. This is an essential property of the arrangement shown in Fig. 5. The use of logarithmic amplitude density scales has several advantages:

1. The relative accuracy over the total recorded probability density range is the same.
2. A wide range can be recorded with sufficient accuracy on a relatively small sheet of paper.

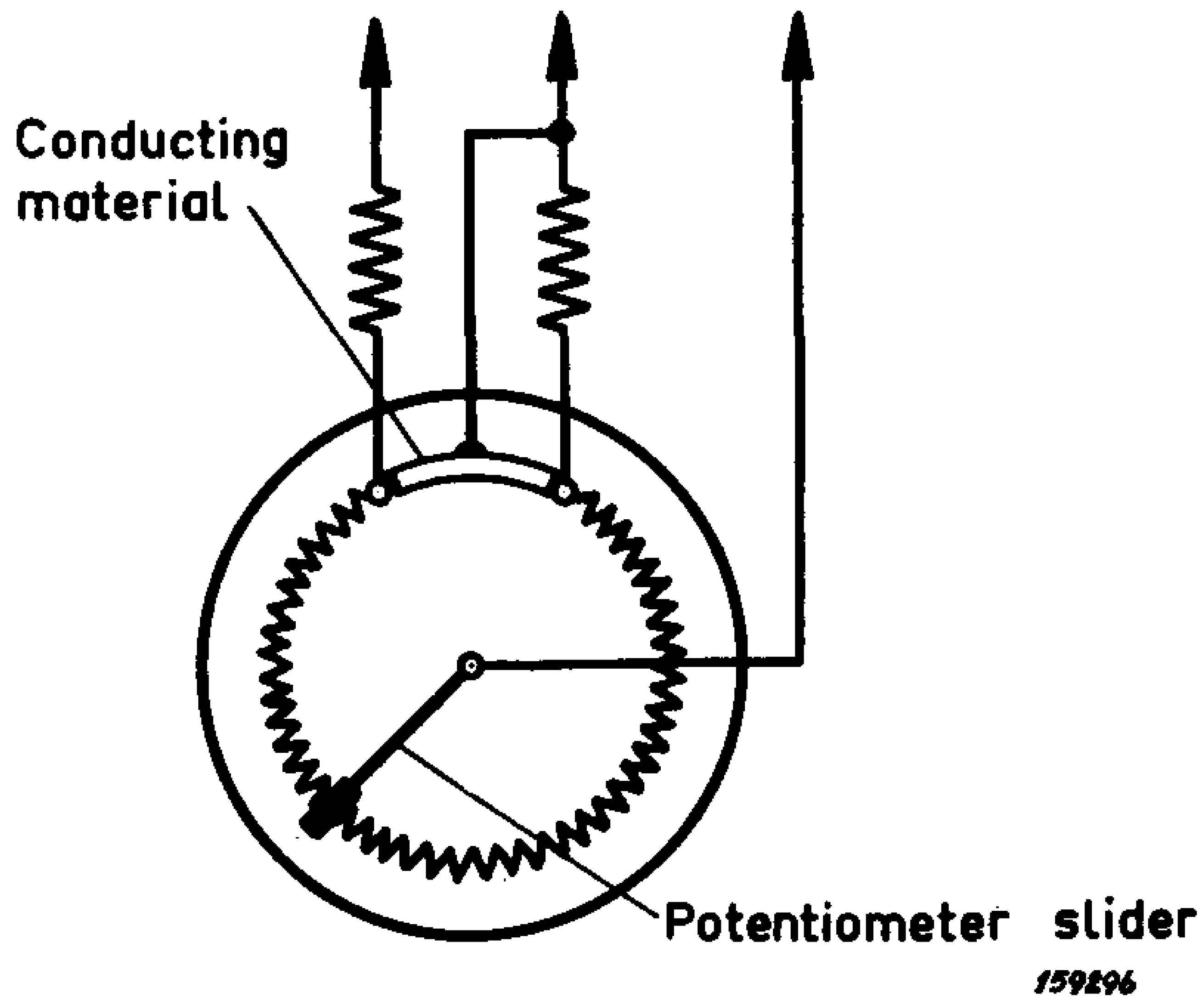

Fig. 6. Sketch illustrating the modification necessary on the Y-position potentiometer of the oscilloscope.

3. The normal (Gaussian) probability density curve will appear as a relatively simple mathematical curve (parabola).

That the Gaussian amplitude density curve will appear as a parabola when plotted on a logarithmic scale is very convenient because it makes it possible

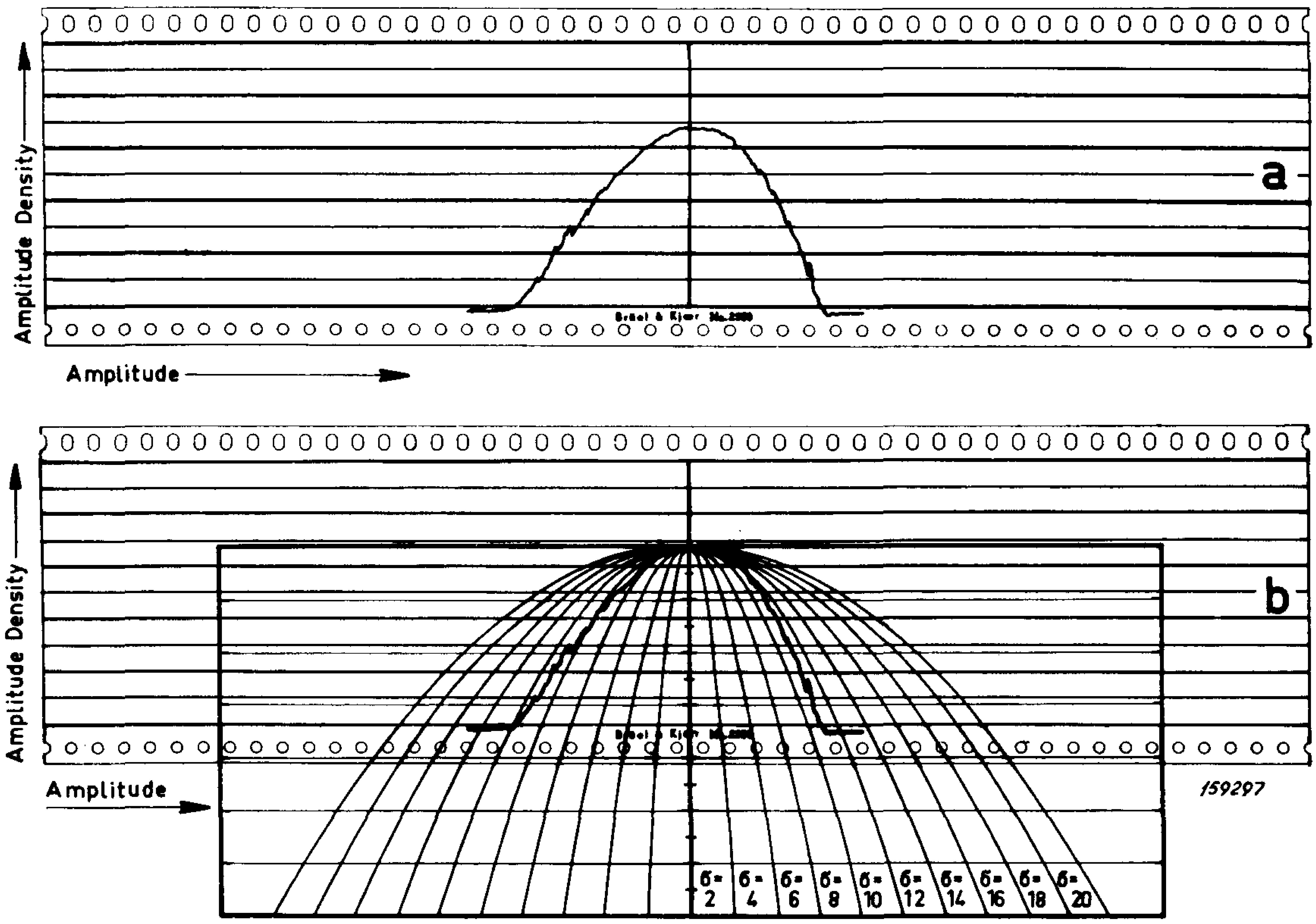

Fig. 7. Amplitude density curve of the wide band output signal from an electronic noise generator.

a. The amplitude density curve.
b. A standard set of parabolas placed on the curve to determine its relation to the normal distribution.

in a quick way to check whether the phenomenon being studied is of a Gaussian nature or if there are any serious deviations.

A set of "standard" parabolas can easily be drawn on a piece of transparent paper and placed on the recorded curve to determine its relation to the normal curve.

Before a further analysis of the measuring arrangement with regard to operating range and calibration is carried out some examples of its application shall now be given.

Fig. 7a shows the amplitude density curve of the wide band output signal from an electrical noise generator, and in Fig. 7b a set of standard parabolas are placed upon the curve.

It can be seen that the signal from the noise generator does not show a completely Gaussian probability distribution (caused by a non-linear noise producing element).

Another important application of the equipment is its use to determine the effect of amplitude clipping of random signals when the signal is passed through electronic and electro-mechanical circuits. This is of special importance in the field of complex motion vibration testing where it is important that the specimen being tested experiences practically true Gaussian distributed stress cycles.

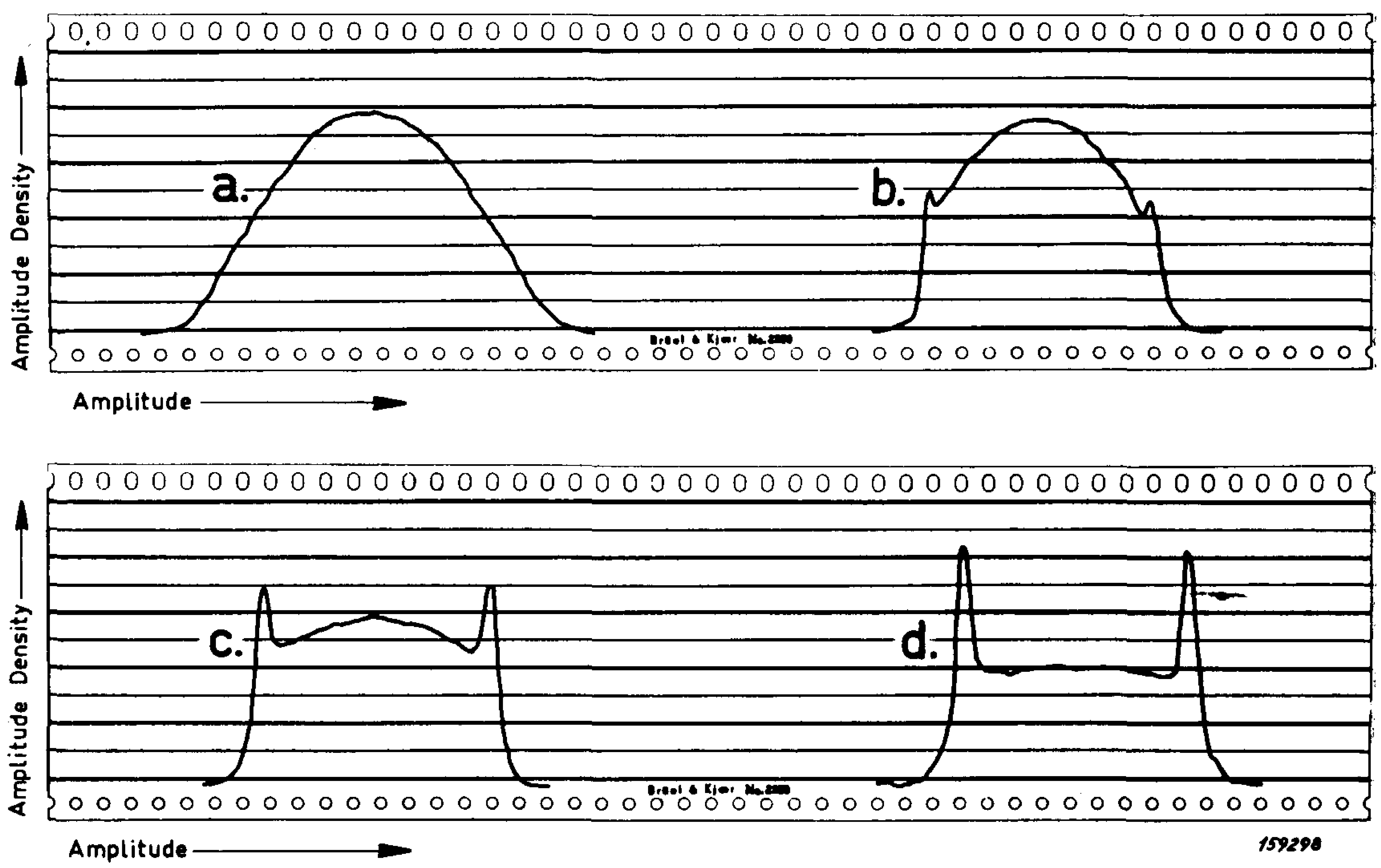

Fig. 8. Records indicating the influence of finite amplitude limiting upon the amplitude density curve.

a. Practically "unclipped" random noise.
b. Slightly amplitude limited random noise.
c. More heavily amplitude limited random noise.
d. Random noise subjected to heavy amplitude limiting.
Note: To obtain clearer curves the scales have been altered during the recording of b through d.

Fig. 8 shows the effect of amplitude limiting upon the amplitude density curve. It is seen that an increase in amplitude density occurs at the limiting level, and that the increase in amplitude density depends, very definitely, upon the degree of limiting.

The concept of amplitude density can of course also be used to characterize periodic phenomena, and in Fig. 9 the amplitude density curve of a symmetrical triangular wave is recorded. The recorded curve follows very closely the theoretical amplitude density curve for this type of signal, as $P\ (x, x + \triangle x) = \frac{\sum_i \triangle t^n}{T}$ must in this case be constant over the entire amplitude range of the wave and zero outside this range.

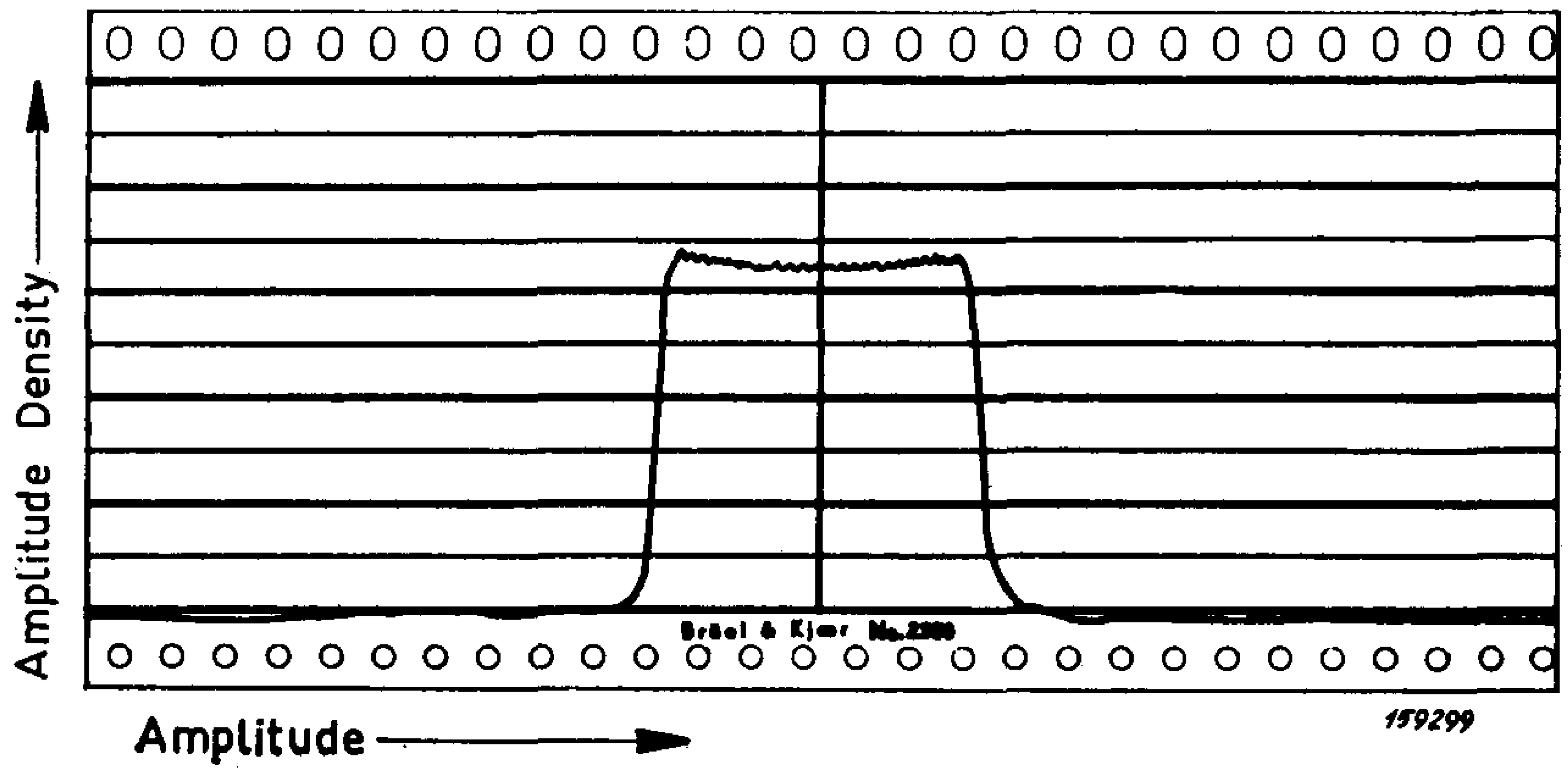

Fig. 9. Amplitude density curve of a symmetrical triangular wave.

By the theoretical treatment of periodic signals with regard to their amplitude density curves it is often very convenient to make use of the fact that the amplitude density is proportional to the time Δt that the signal requires to increase its amplitude an amount Δx, i. e. inversely proportional to the "velocity" of the change in amplitude from x to x + Δx. Mathematically this can be stated:

$$p\ (x) \sim \frac{\triangle t}{\triangle x} \rightarrow \frac{dt}{dx} \rightarrow \frac{1}{\frac{dx}{dt}}$$

For example in the case of the above mentioned amplitude density curve for the triangular wave $\frac{dx}{dt}$ is constant over the entire amplitude range of the signal.

Fig. 10 shows the amplitude density curve of a square-wave signal. In this case $\frac{dx}{dt} = 0$, i. e. $p(x) = \infty$ for amplitudes equal to the peak value of the wave, and zero outside exactly those amplitude values. Due to the finite width of the trace

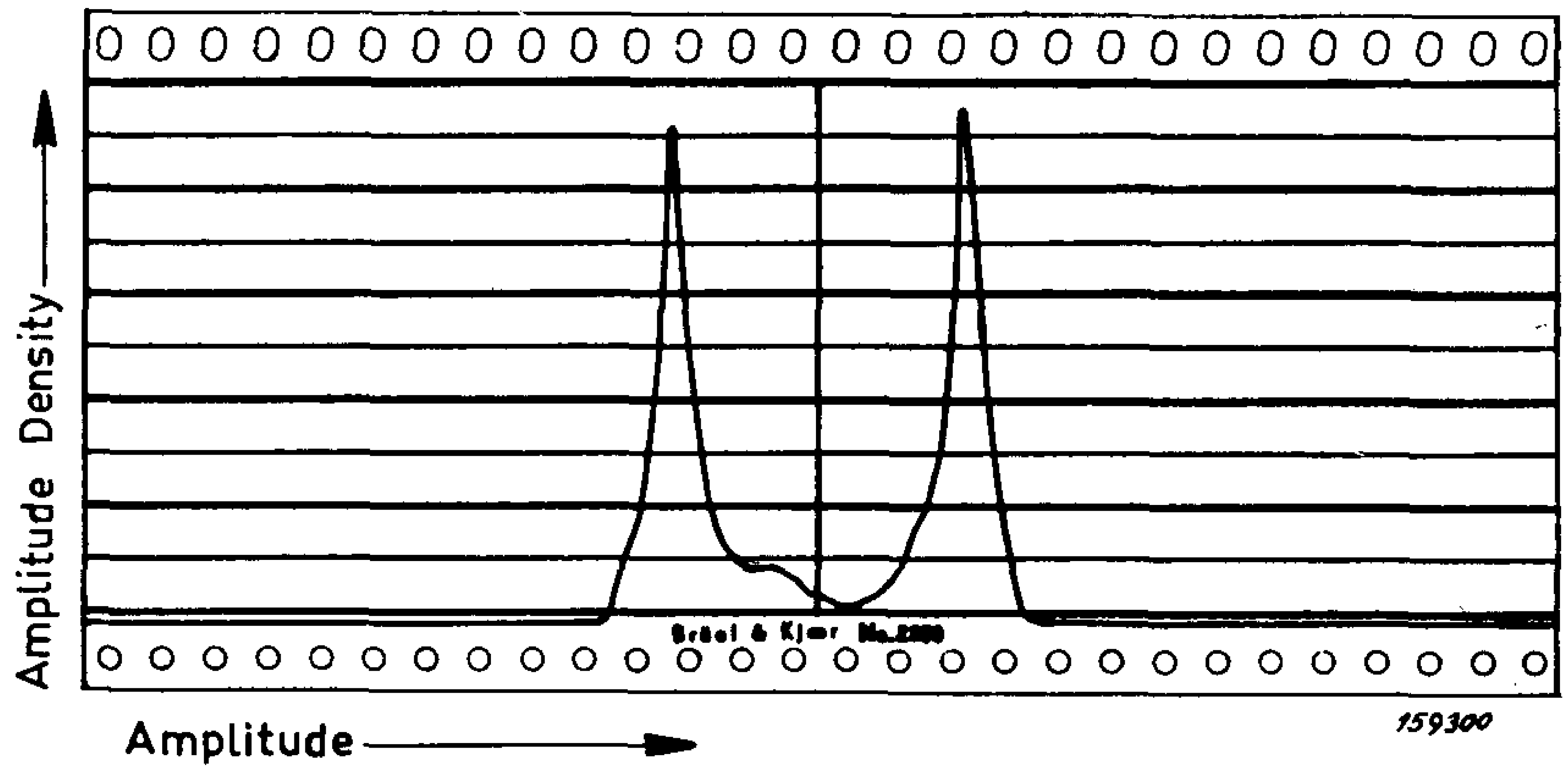

Fig. 10. Amplitude density curve of a square-wave signal.

on the oscilloscope and the width Δx of the slit in front of the photomultiplier unit the theoretical values can never be completely reached, but an excellent idea of the type of distribution being measured is obtained in most cases.

A further example of the use of the instrumentation is shown in Fig. 11. The input signal here is a signal of sinusoidal waveform. Again the differential $\frac{dx}{dt}$ gives a hint to the theoretical shape of the amplitude density curve, which, of course, should be infinite at the peak amplitudes of the wave, and have a certain finite value during the zero-line crossing.

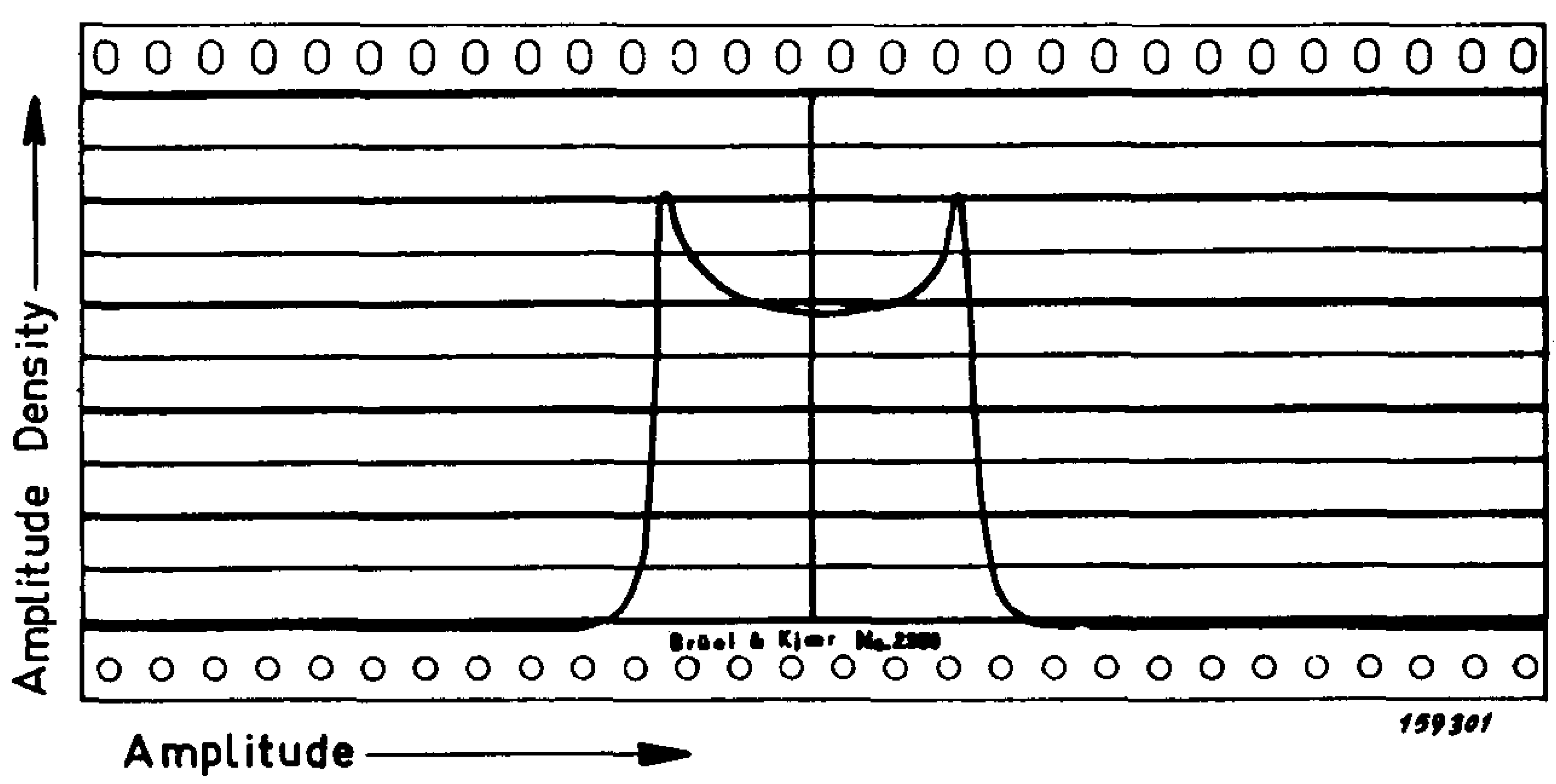

Fig. 11. Amplitude density curve of a sinusoidal signal.

The periodical signals whose amplitude density curves are shown in Figs. 9 through 11 were all derived from an electronic function generator.

When signals having continuous frequency spectra are studied it is often of considerable interest to determine the amplitude density curve for different frequency bands throughout the spectrum, whereby otherwise hidden anomalies might be detected.

This can be done very conveniently with the arrangement shown in Fig. 5 when a B & K frequency analyzer of the type 2110 (A.F. Spectrometer) is added to the arrangement, (see Fig. 12).

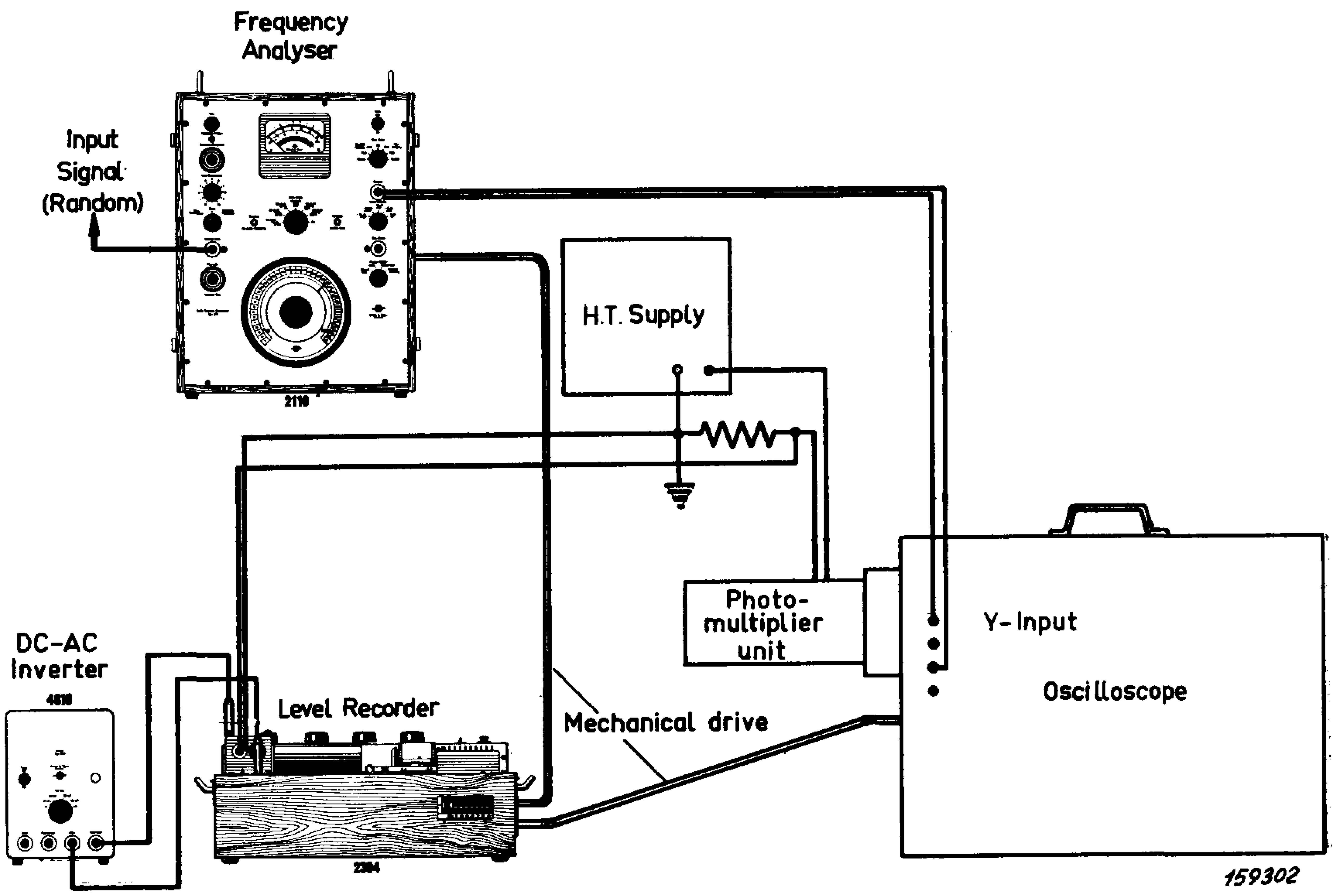

Fig. 12. Measuring arrangement for the automatic amplitude density analysis of random signals.

The electrical input signal to the oscilloscope is then divided into ⅓ octave frequency bands, and each frequency band can be investigated separately. By driving the frequency sweep of the spectrometer directly from the second spindle of the level recorder motor the spectrometer will automatically switch to its next filter when one rotation of the spindle is completed. *This again means that the complete set of amplitude density curves, one for each of the spectrometer filters, can be recorded automatically.*

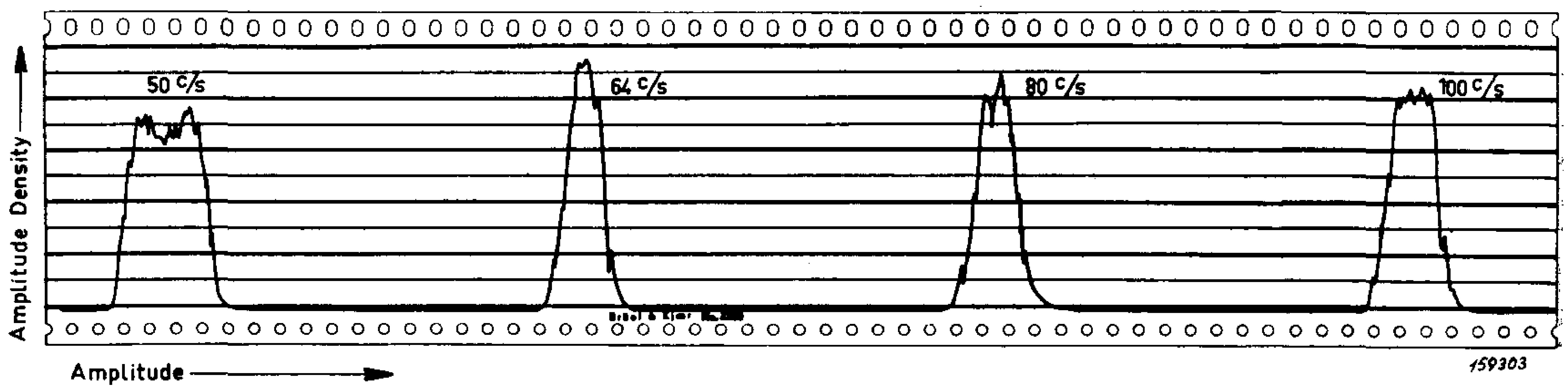

Fig. 13. Amplitude density curves obtained from measurements at low frequencies, ⅓ octave bandwidths.

Figs. 13 and 14 show some typical curves recorded in this way. The measurements were made on the same noise generator as mentioned earlier in this article. Fig. 13 shows a set of amplitude density curves obtained from measurements at low frequencies where the tendency towards sinusoidal distribution will be clearly seen, especially in the 50 c/s and 100 c/s filter bands.

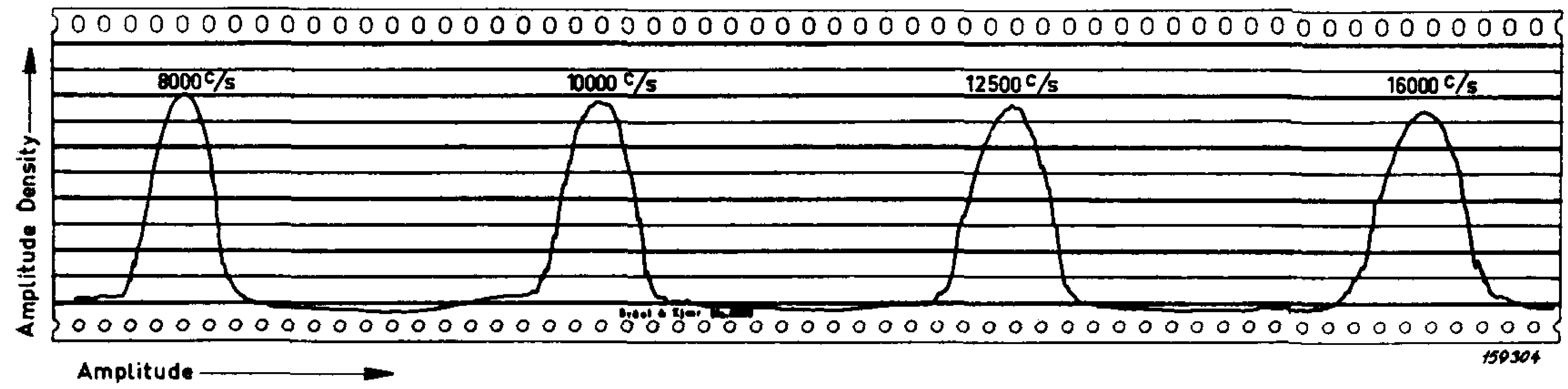

Fig. 14. Amplitude density curves obtained from measurements at higher frequencies, 1/3 octave bandwidths.

Fig. 14 shows similar curves for higher frequencies and in this case the probability distribution of the amplitudes is almost perfectly Gaussian, see also Fig. 15.

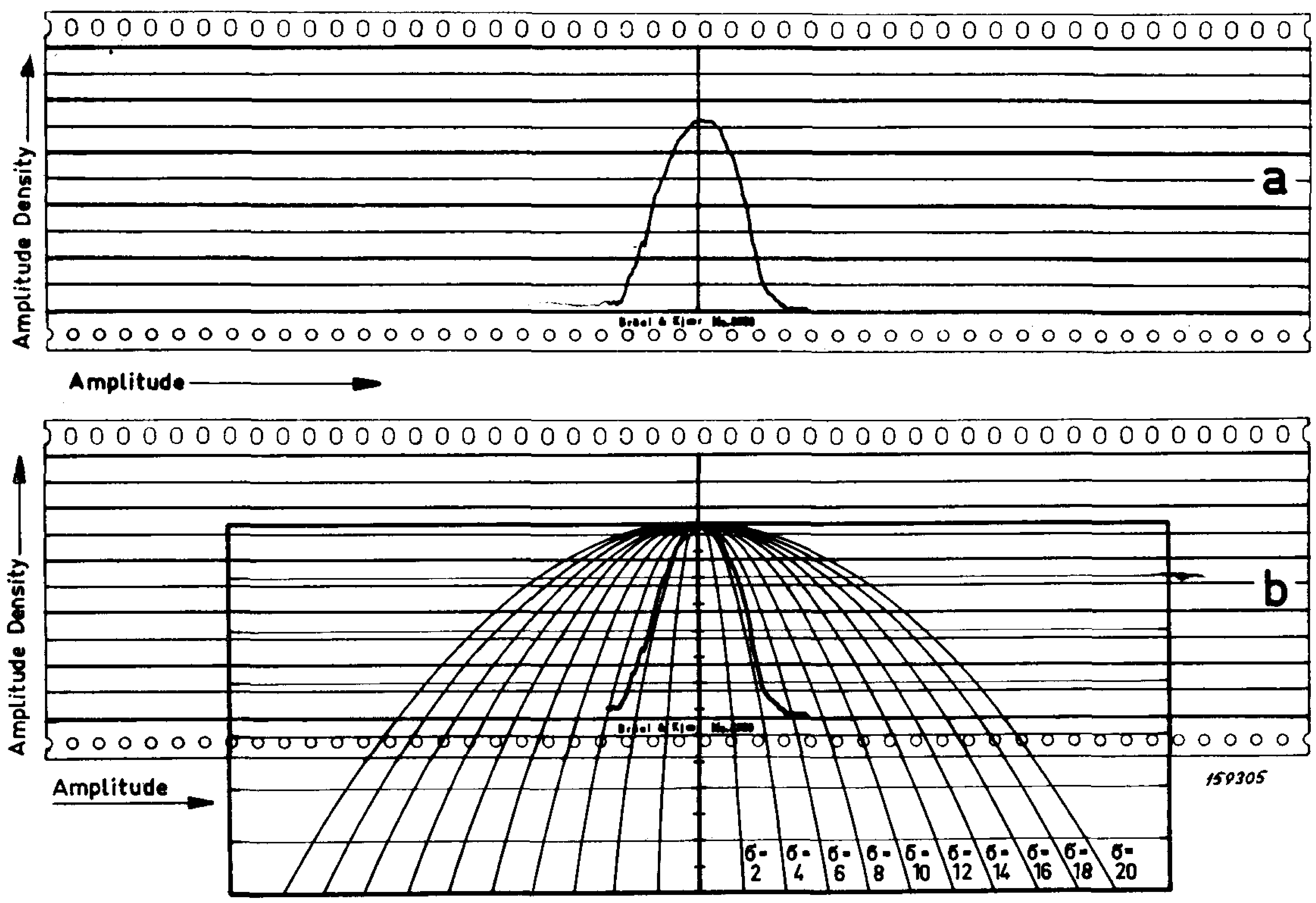

Fig. 15. Amplitude density curves obtained from measurements on filtered noise (cfr. Fig. 14).
a. The amplitude density curve.
b. A standard set of parabolas is placed on the curve. Note the almost perfect Gaussian distribution of the amplitudes.

Before closing this article some remarks regarding the calibration and limitation of the arrangements described should be given.

The calibration should preferably be made in two steps:

1. Finding the position of the zero crossing axis ($x = 0$).
2. Calibrating the recording paper in volts per mm, and relating this calibration to the actual process being studied.

To find the position of the zero-crossing axis it is only necessary to record the amplitude density curve of the light from the oscilloscope when no signal is applied to its input. By recording two successive sweeps on the screen two peaks are recorded as shown in Fig. 16. The distance between the two peaks is then the distance between the zero crossing axis of the curves. If now the amplitude density curve of the process involved is recorded without changing the settings of the level recorder the zero crossing axis can be readily drawn in on the chart as in Fig. 16. Other calibration methods may be found, but this method has proved to be very simple and sufficiently accurate.

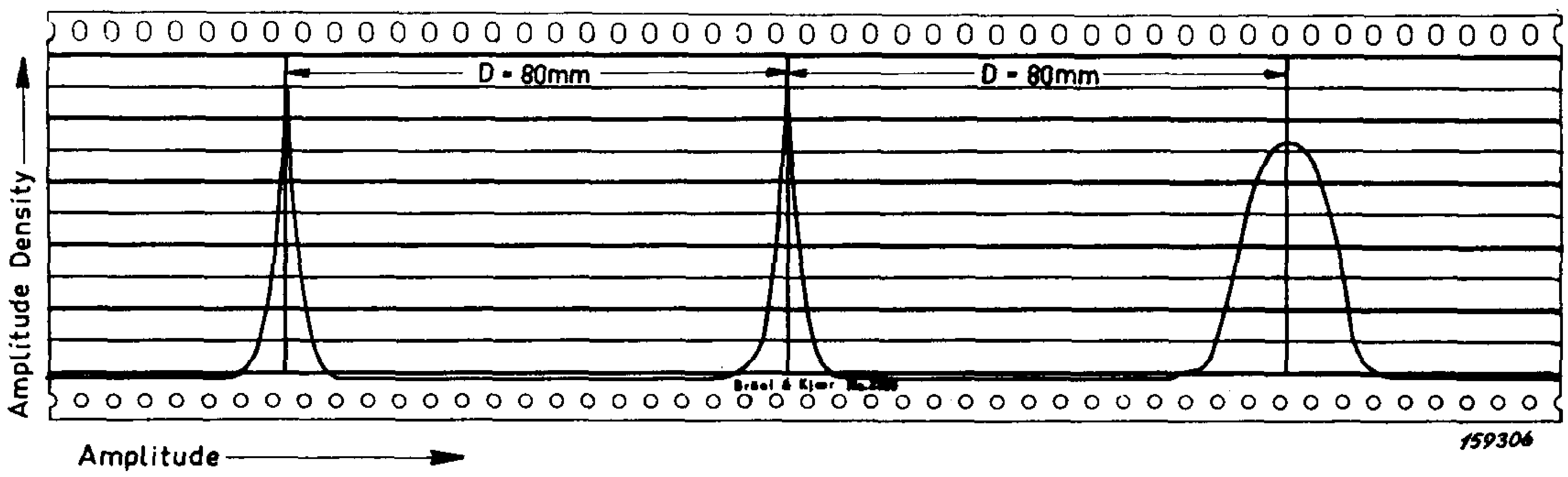

Fig. 16. Example of determining the mean value of a random signal.

To calibrate the recording in volts per mm the easiest method is to apply a sinusoidal signal of known amplitude value to the oscilloscope and record the amplitude density curve (without changing the settings of level recorder). The distance between the two maxima equals the *peak-to-peak* value of the sine wave, and by measuring this distance in mm and the peak-to-peak value in volts the desired calibration is obtained directly by division, see also Fig. 17.

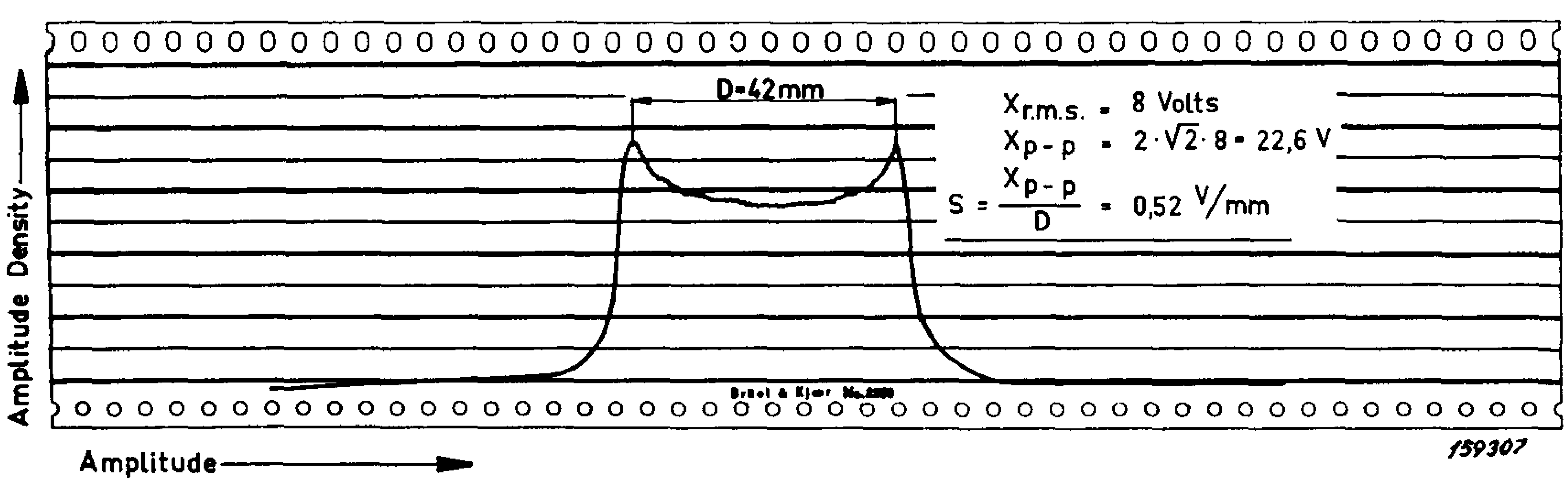

Fig. 17. Calibrating of the record in volts/mm.

The standard deviation of any signal can be measured directly on one of the B & K true r. m. s. measuring instruments 2107, 2110, 2409, 2603 or 2604. These instruments also enable direct measurement of the arithmetic average deviation from the mean.

With regard to the limitation of the described measuring arrangements the dynamic range of the probability density curve is normally limited by the properties of the fluorescent screen of the cathode ray oscilloscope. The lower limit will be set by reflections of the photons in the glass bulb of the tube causing "false" light to arrive at the photomultiplier, while the upper limit is determined by saturation of the fluorescent material. It has not been possible with commonly available cathode ray tubes to obtain a greater dynamic range of the probability density measured than 40 db (100:1). However, by means of specially made cathode ray tubes (and improved circuitry, see Appendix) this range might be considerably extended.

If such tubes are used the limitation of the recording equipment in the arrangements described would be around 75 db (5450:1) as set by the level recorder (and inverter).

The accuracy of the recorded amplitude density curve will depend upon the width Δx and length L of the slit in the photomultiplier unit as well as the settings of the level recorder control knobs and the sweep rate used. Excellent treatments on the accuracies obtainable in random noise and vibration measurements are given by S. O. Rice (2), J. S. Bendat (4) and C. T. Morrow (5).

If desired, specific parts of the amplitude density curve can also be examined separately by using a 25 or 10 db input potentiometer on the level recorder. The fine resolution provided by this arrangement might be of greatest interest for investigations of the amplitude distribution around the zero-crossing axis. The sweep speed of the oscilloscope and the paper drive of the level recorder can, furthermore, be adjusted separately whereby almost any degree of accuracy can be obtained by the recording itself.

APPENDIX.

Proposed Circuitry for Increased Dynamic Range of Amplitude Density Instrumentation.

The dynamic range of 40 db might in many cases be insufficient when a thorough investigation of amplitude density curves is to be carried out. It has therefore been found necessary to improve the technique, first by introducing a cathode ray tube with an afterglow of only a few microseconds (10 % light limit), and then by reducing the effect of the dark-current in the photomultiplier tube.

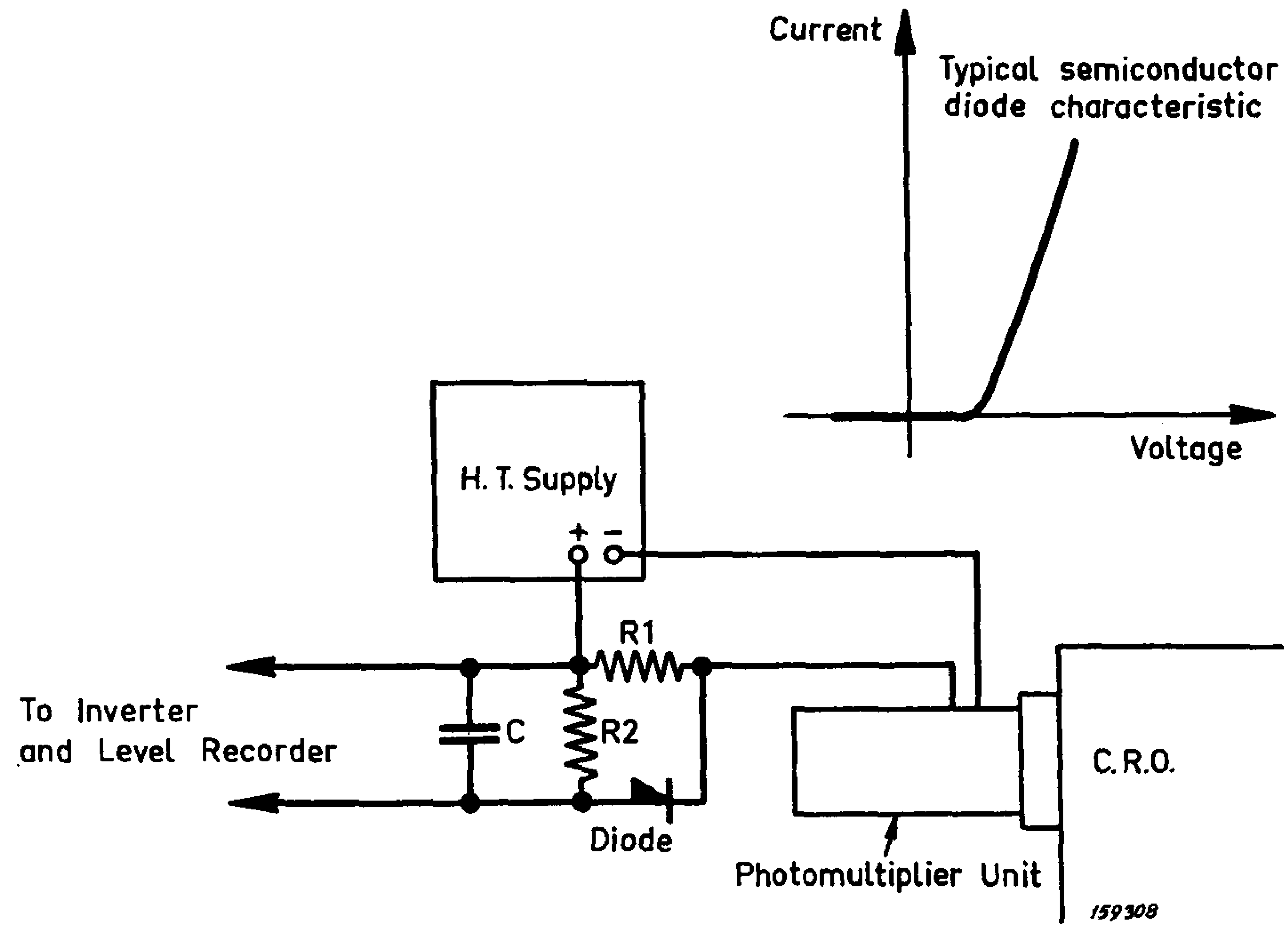

Fig. A1. Proposed circuitry to obtain a greater dynamic range of the amplitude density measuring equipment.

A convenient circuitry which will almost eliminate the signal from scattered photons and undesired secondary emission is shown in Fig. A. 1.

Because the diode needs a certain voltage to "open" (in the order of 0.2—1 volt) the voltage produced by undesired emissions in the photomultiplier will not be great enough to "open" it and consequently no current caused by these emissions will flow through the resistor R2 and be measured.

However, when the cathode ray beam passes the narrow slit in the photomultiplier unit pulses of a certain height (determined by the light intensity of the beam) but of different widths will be produced. The height of the pulses is great enough to produce a voltage which opens the diode, and the width of the pulses now determines the average value of the voltage developed across R2. The very short afterglow required from the cathode ray tube is necessary to avoid integration of the light-pulses on the screen of the C. R. tube itself.

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News from the Factory.

Exiter Control Preamplifier Type 1608.

The Exiter Control Preamplifier Type 1608 is designed specifically as a two function preamplifier for connection between the B & K Accelerometer Type 4330, as supplied with the Accelerometer Sets 4310 and 4350 and the B & K Automatic Vibration Exiter Control Type 1016 used in vibration test arrangements.

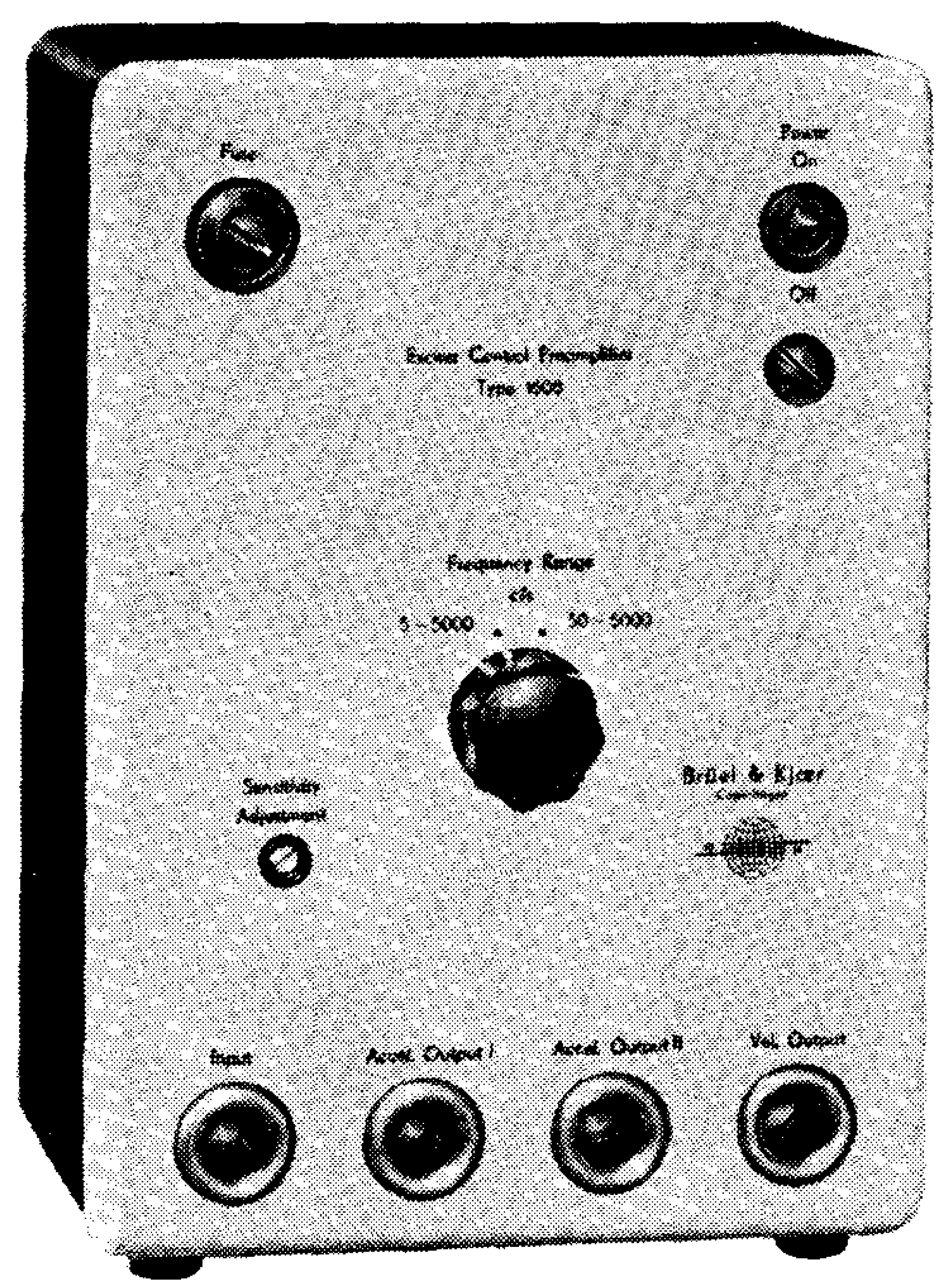

Photo of the Preamplifier Type 1608.

When the 1608 is used in conjunction with the Accelerometer 4330 and the Exciter Control 1016, the combination offers facilities for constant acceleration, constant velocity or constant displacement operation of the shaker table, controlled directly from the accelerometer. Frequency range of the 1608 is 5-5000 c/s.

The preamplifier may also be used separately from the 1016 providing a high impedance input of approximately 500 MΩ, a velocity and an acceleration output having impedances which should be matched to 100 kΩ, as well as a special acceleration output with an impedance of 2000 Ω. Using the special acceleration output, the frequency range of the instrument is linear to within $\pm$ 0,5 db from 2 to 10,000 c/s with loads less than 1200 $\mu\mu$F and output voltage $<$ 10V R.M.S.

The 1608 is very simple to install and is self powered from the supply line.

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