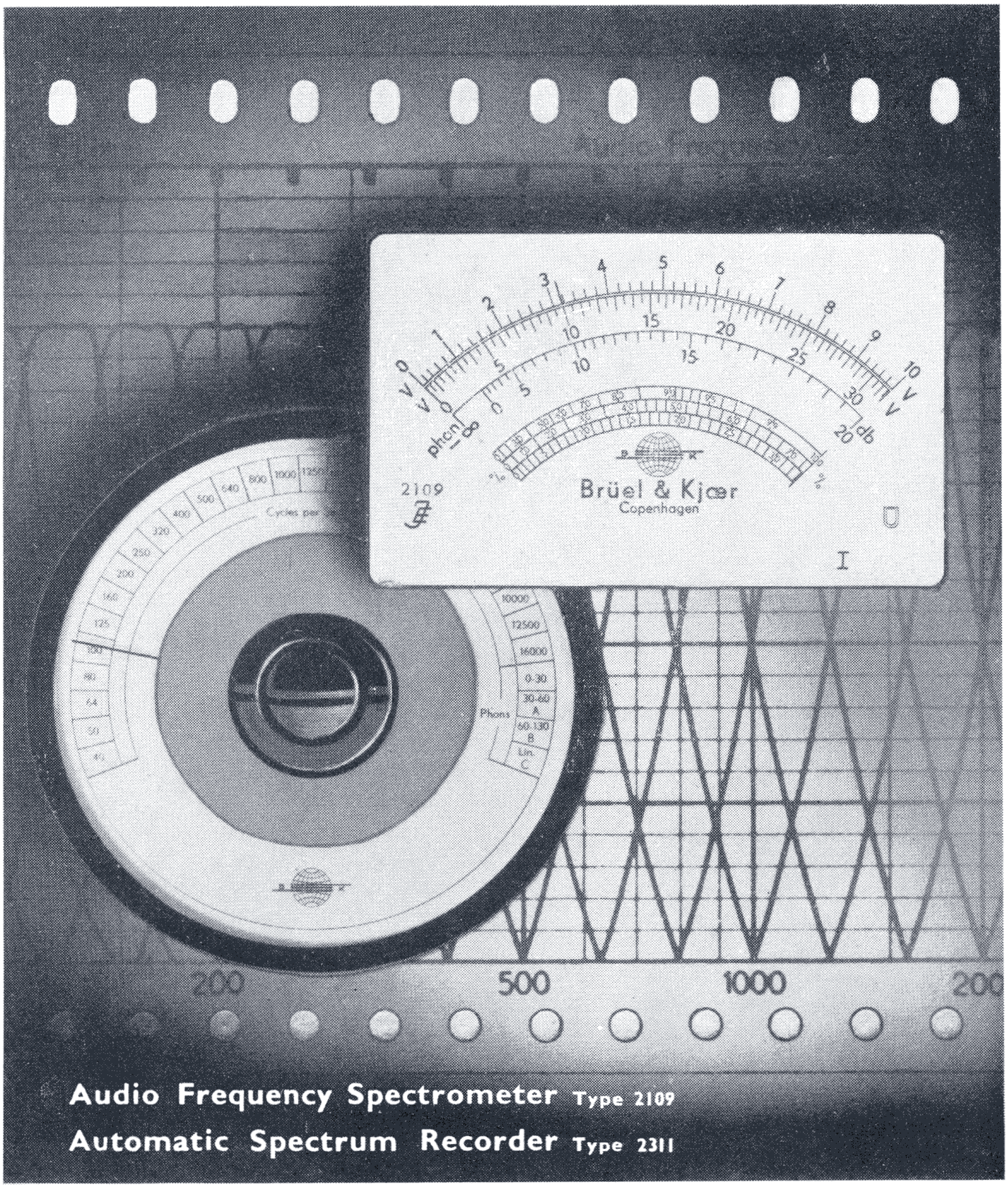
Brüel & Kjær

Technical Review

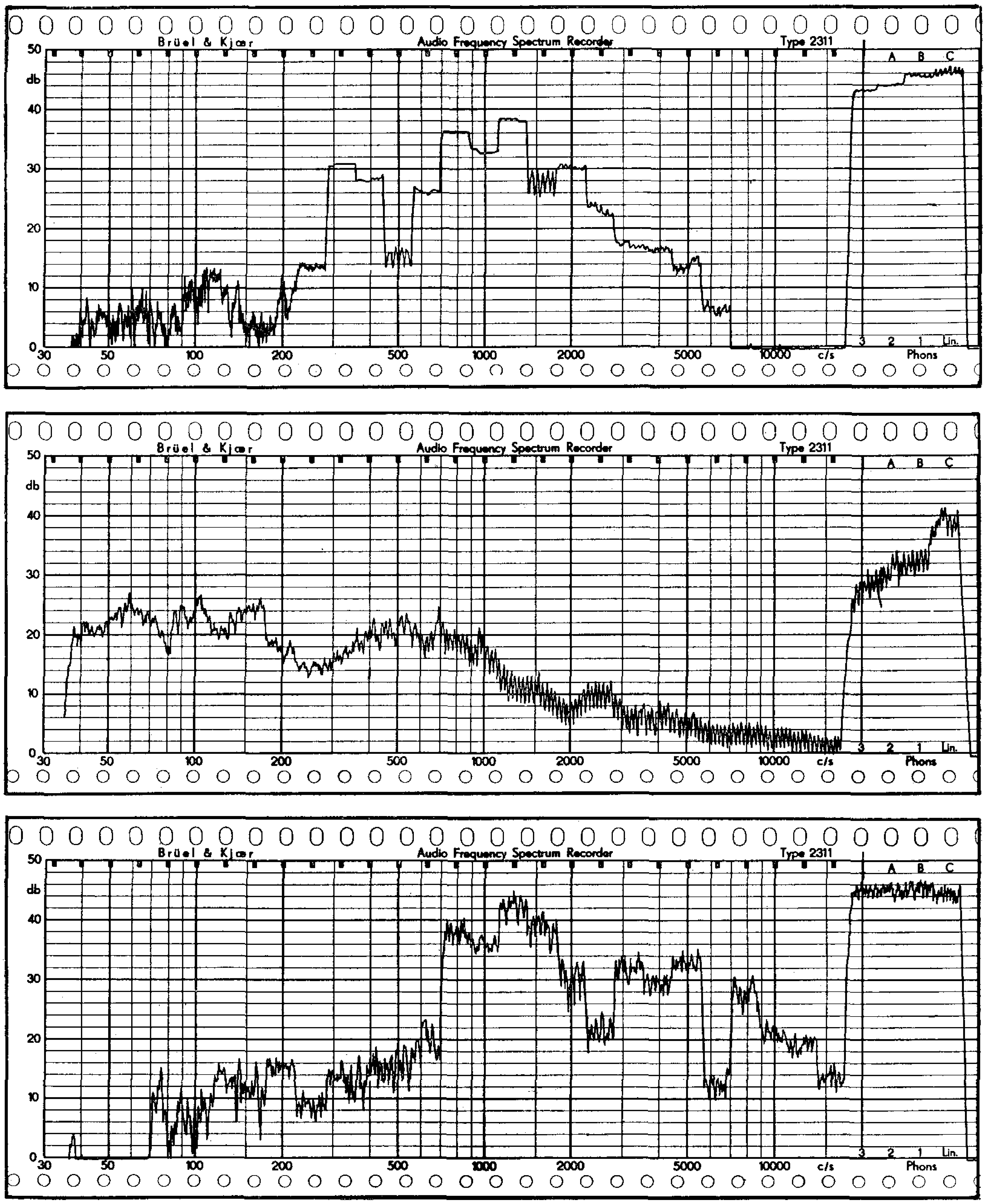
Teletechnical, Acoustical and Medical Research



No. 4

October 1953

This number of our Technical Review is completely devoted to a new instrument, extending our series of apparatus for acoustic measurements, the **Audio Frequency Spectrometer type 2109.** *This instrument, together with our* **High Speed Level Recorder type 2334,** *also results in a new type Recorder, the* **Automatic Spectrum Recorder type 2311,** *which makes possible the automatic recording of all kinds of noise spectrograms, and analyses of vibrations. A description of both instruments will be given, together with a number of typical applications.*



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Spectrogram of

1) Double toned automobile horn. Zero level: 1 μbar.

2) Watch P7R 12348. Distance 50 cms. Zero level: $6 \cdot 10^{-4}$ μbar.

3) Alarm clock ringing. Zero level: $2 \cdot 10^{-2}$ μbar.

(Fig. 21, s. page 20)

AUDIO FREQUENCY SPECTROMETER

Type 2109

AUTOMATIC SPECTRUM RECORDER

Type 2311

The Spectrometer type 2109 is primarily designed as a universal tool for acoustical and electro-acoustical measurements, as for example working out vibration and noise spectograms, measurements of sound pressures, noise and vibration levels, and as selective amplifier when measuring reverberation times.

However, the instrument can be used with great advantage in pure electrical measurements, for example as indicator in bridge measurements and to analyze complex voltages.

The Spectrometer is designed to meet the demands drawn up by the "working committee" for the standardization of the measurements of sound transmission in the code of July 1949 and verified in May 1950 and consists of a preamplifier, followed by 27 third-octave filters and 3 weighting networks.

A switch after the filters can either automatically or manually select the 30

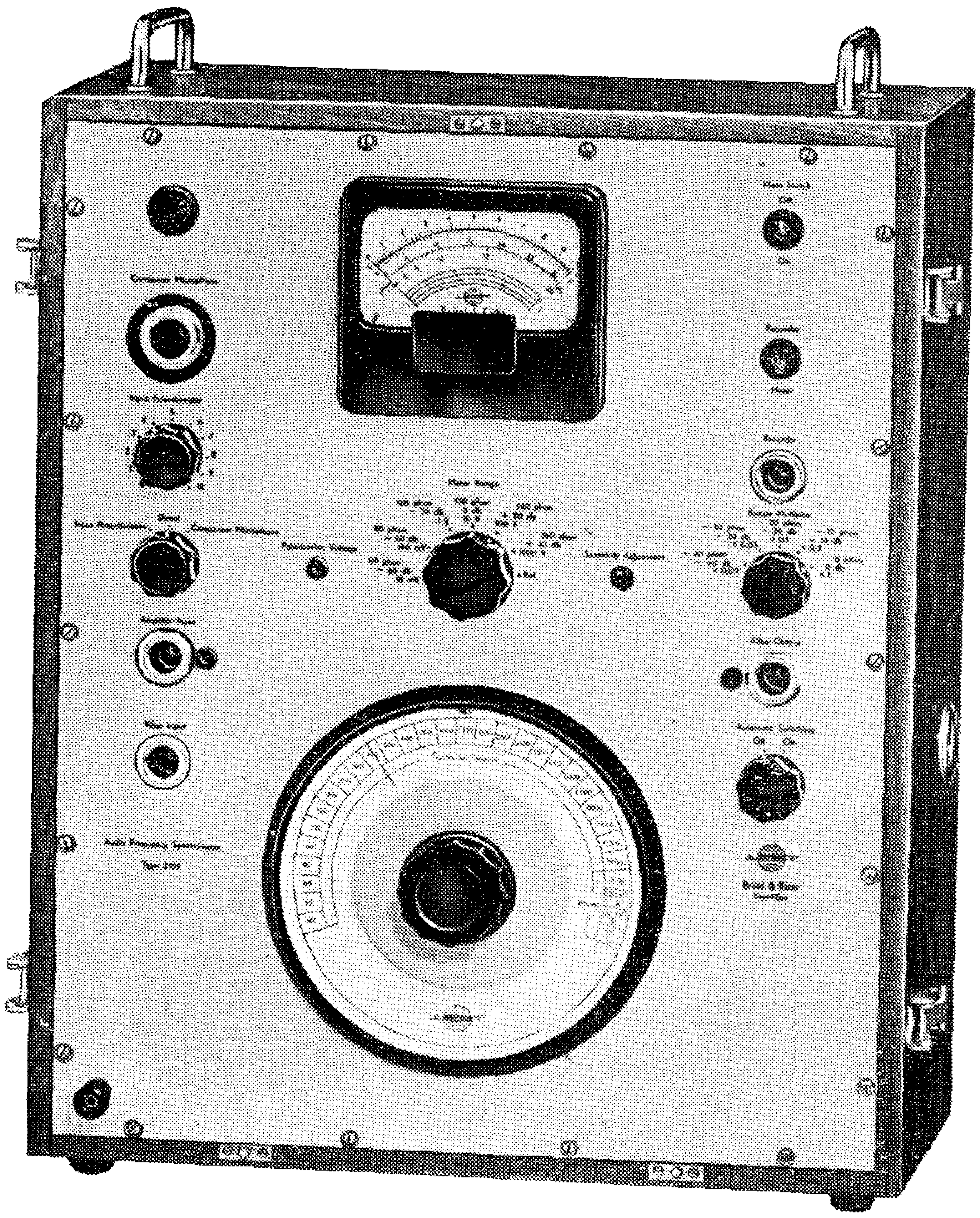

Fig. 1. Photo of the Audio Frequency Spectrometer type 2109.

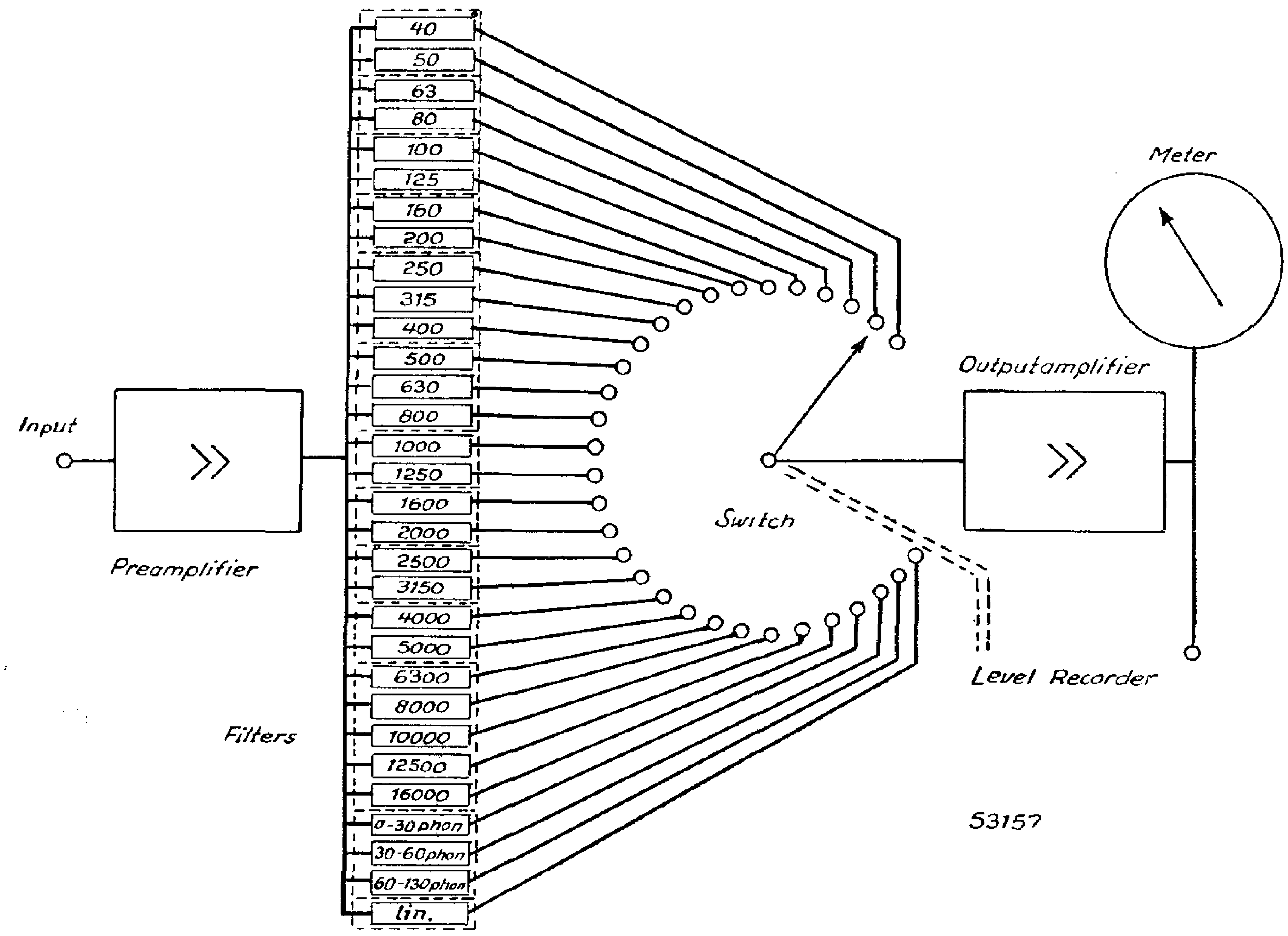

Fig. 2. Schematic diagram of the Spectrometer 2109.

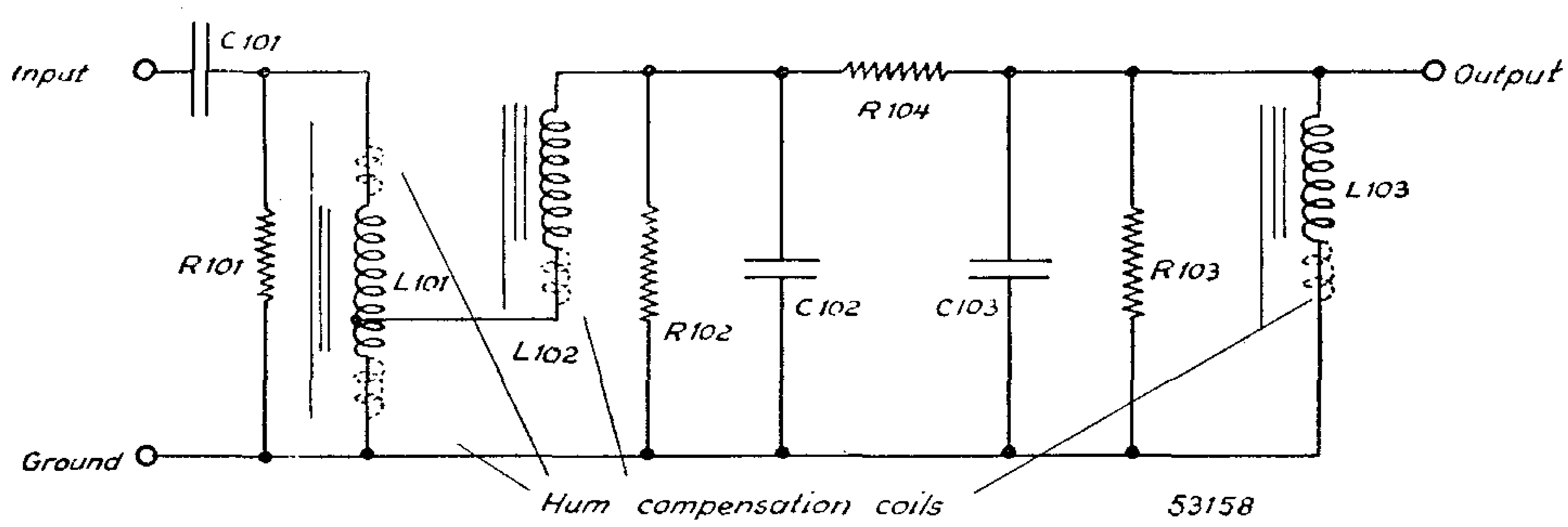

Fig. 3. Diagram of a third-octave filter unit.

filters to the output amplifier, which drives either the meter of an external instrument, as for example the Level Recorder 2304.

Each filter consists of three resonance circuits, of which the first two, with a quality factor Q = approx. 10, and a coupling factor K = 0.2, will give a double humped resonance curve, while the third, with a Q = approx. 5. K = 0.05, will give a single top which will raise the valley between the two humps on the first curve, with a total result as shown in fig. 5, a $^1/_3$ octave pass-filter with a flat top and very steep sides.

Because the quality factor will vary somewhat with the frequency the two tops in fig. 4 left will not have the same height. The third resonant frequency must therefore be placed unsymmetrically to obtain a horizontal top. This top will therefore not be symmetrical but will have two humps, a broad one and a narrow one.

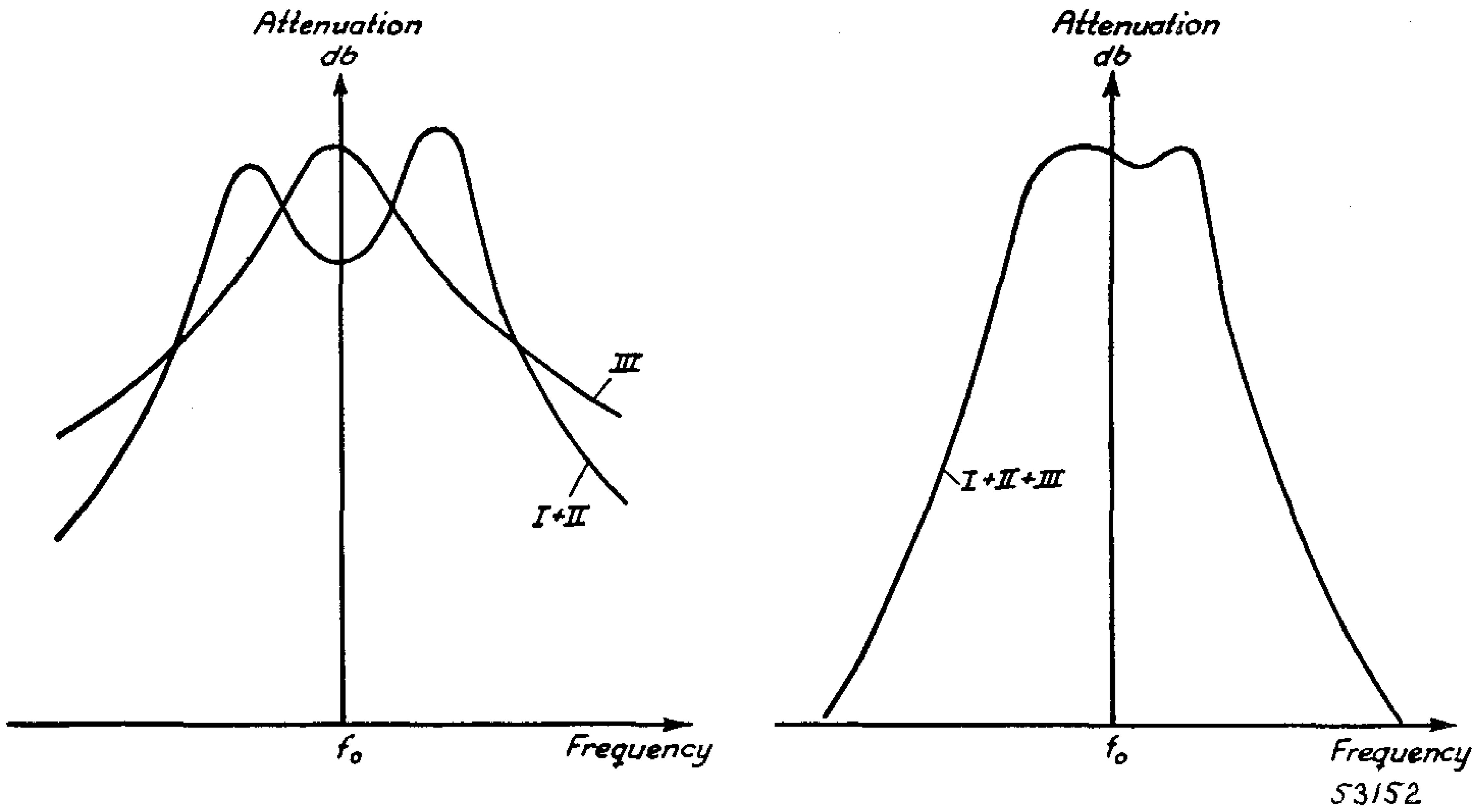

Fig. 4. Characteristics for filter unit.

The 27 filters have mid-frequencies at 1/3 octave distance. The frequencies are 40 — 50 — 63 — 80 — 100 — 125 — 160 — 200 — 250 — 315 — 400 — 500 — 630 — 800 — 1000 — 1250 — 1600 — 2000 — 2500 — 3150 — 4000 — 5000 — 6300 — 8000 — 10000 — 12500 — 16000 c/s. The figures are the so-called preferred numbers which are standardized in most countries. The figures given here are the rounded-off values. The exact values are numbers whose logarithms are integral multiples of 0.1, i. e. whose mantissae are exactly 0.1, 0.2, 0.3 etc.

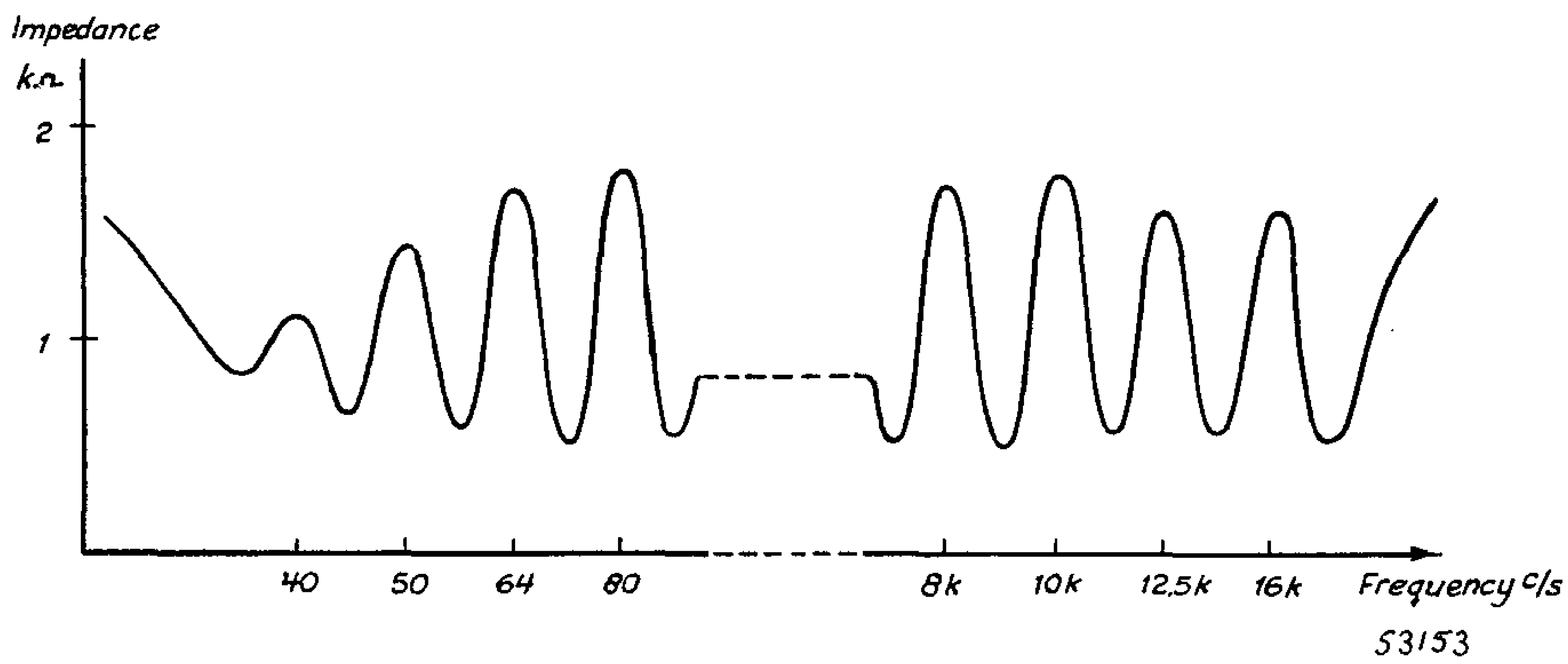

Fig. 5. Variation of input impedance of the filter section.

The filters can also be used without preamplifier or output amplifier, for which purpose two special jacks are placed on the front plate, inscribed "Filter input" and "Filter Output". Care should be taken in these cases to have the output impedance of the measuring object low in relation to the 35—70 kΩ

The top is "flat" within ± 1/2 db for about 1/4 octave. The attenuation at the band limits ± 1/6 octave from the middle is about 3 db, normally a little lower. See fig. 6. However, because of the great steepness of the filter curve at this point, one cannot expect the responses of two neighbouring filters to cross at about 3 db. For example, if the mid-frequencies of two neighbouring filters are displaced only 1 % in opposite directions, the cross-point will be about 1.7 db higher or lower, or if the width of the filter curves are altered 1 %, the cross-point will be about 0.2 db higher or lower.

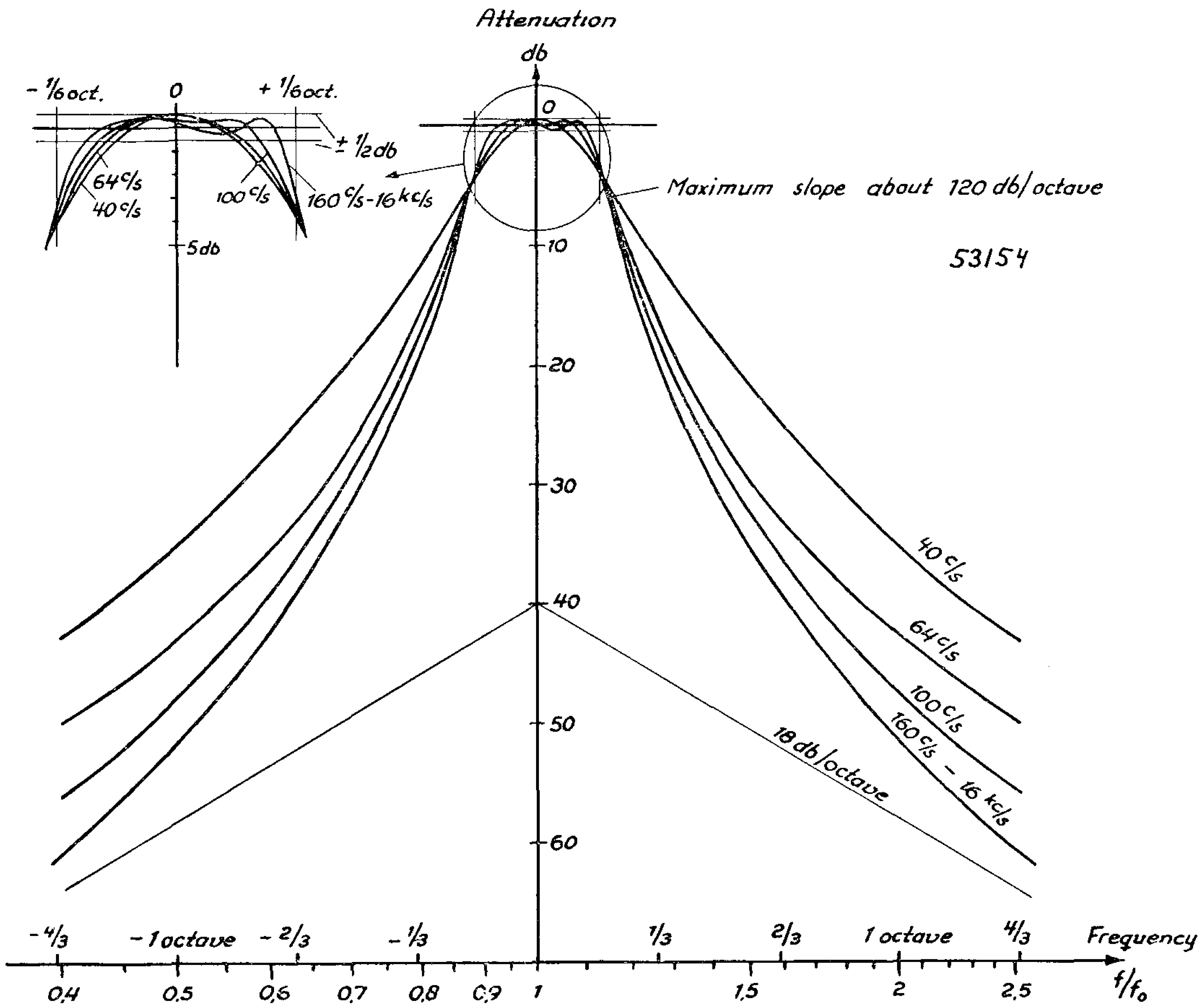

Fig. 6. Detailed filter characteristics.

The attenuation at ± 1/3 octave from the middle is adjusted to about 20—21 db. The filter curve will then be as shown in fig. 7 with an attenuation of about 52 db at ± 1 octave.

However, it has been impossible to obtain sufficiently high quality factors for the coils at frequencies under 160 c/s, without lowering the stability or making the filters bigger and heavier. Thus the filter curves will be gradually worse for lower frequencies as seen in fig. 6 and 7. There will thus only be one top, and the "flat" part is only about 1/6 octave. The attenuation is up to 4 db at the band limits, from 12 to 20 db at ± 1/3 octave and from 35 to 50 db at 1 octave from the middle frequency.

As far as the lower frequencies are concerned it appears that magnetic fields from nearby mains transformers, electrical machinery and so on can induce quite considerable hum voltages in the coils even though these are placed in sealed pot-cores. It has therefore been necessary to place some coils outside

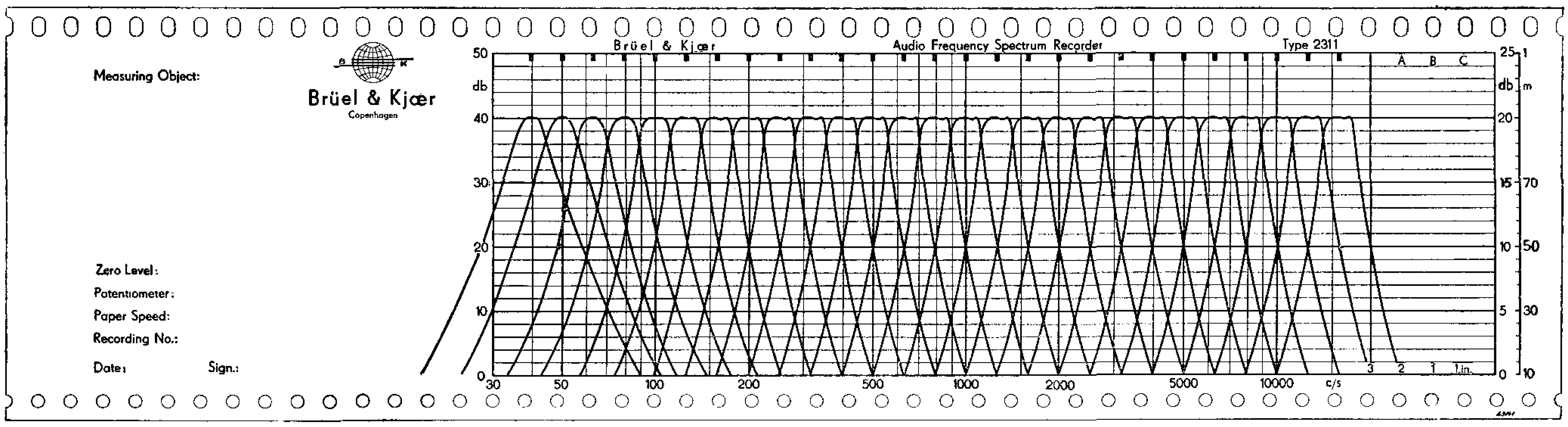

Fig. 7. The practical third-octave filter curves.

the pot-cores and to connect these compensation coils as indicated in fig. 3, so that the hum voltages are reduced by a factor of 10 or more.

With regard to the phone filters these are so constructed that the curves shown in fig. 9 are obtained, which satisfy both the German DIN 5045 and the American ASA Z 24.3 Standards for Objective Sound Level Meters. The difference between these two standards is only noticeable for frequencies under 100 c/s. Moreover, the tolerances permitted both for the European and American Standards are so great that it is possible to give an instrument frequency characteristics with satisfy both standards' requirements.

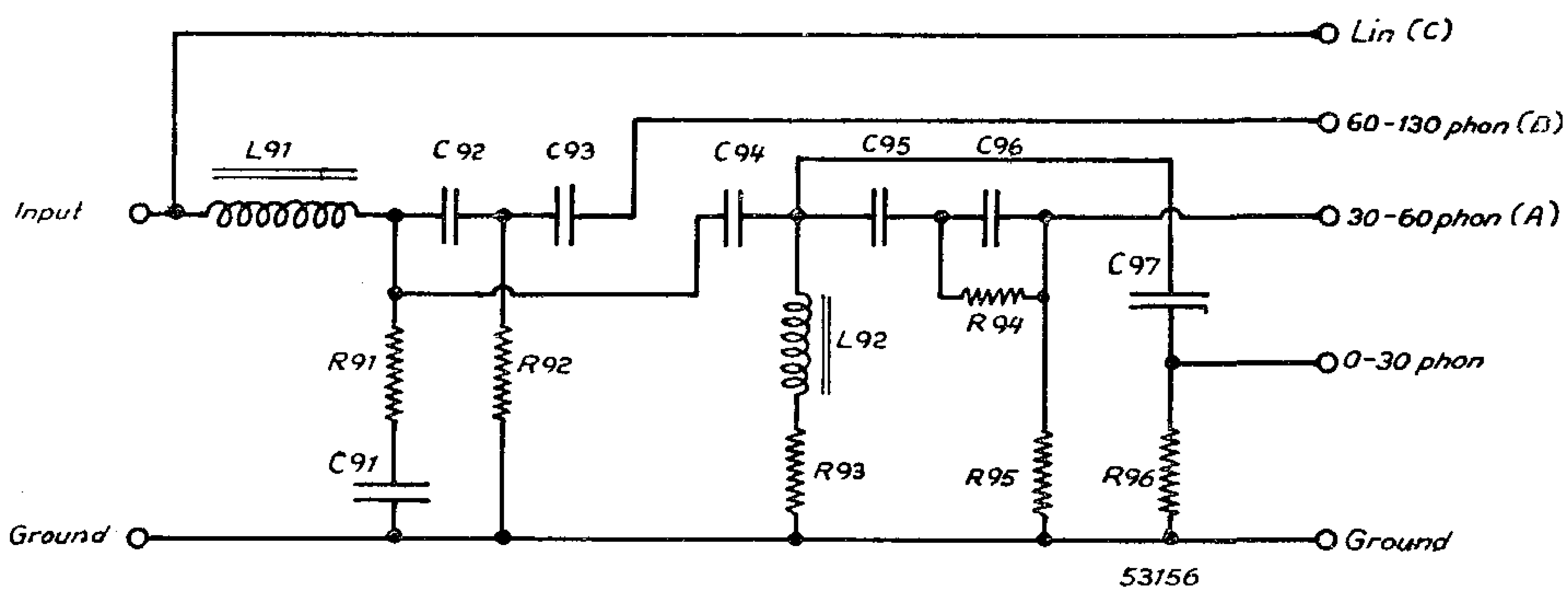

Fig. 8. Weighting networks for noise level measurements.

The complete Audio Frequency Spectrometer type 2109 contains, besides the above described third-octave filters with automatic switching, an input amplifier, an output amplifier, and the necessary rectifiers for operating these amplifiers as well as feeding the cathode-follower in a connected Condenser Microphone type 4111.

The purpose of the input amplifier is to adjust the signal voltage at the input terminals of the filter to approx. 1 volt. It consists of a two stage amplifier, transformer coupled to the filter, and by means of a very powerful negative feed-back it has been possible to obtain a value of approx. 25 ohms for the impedance coupled to the filter, while at the same time the amplifier can supply approx. 1 volt to the filter with a maximum distortion factor of 1 part in 100. The two amplifier tubes and corresponding coupling components are mounted

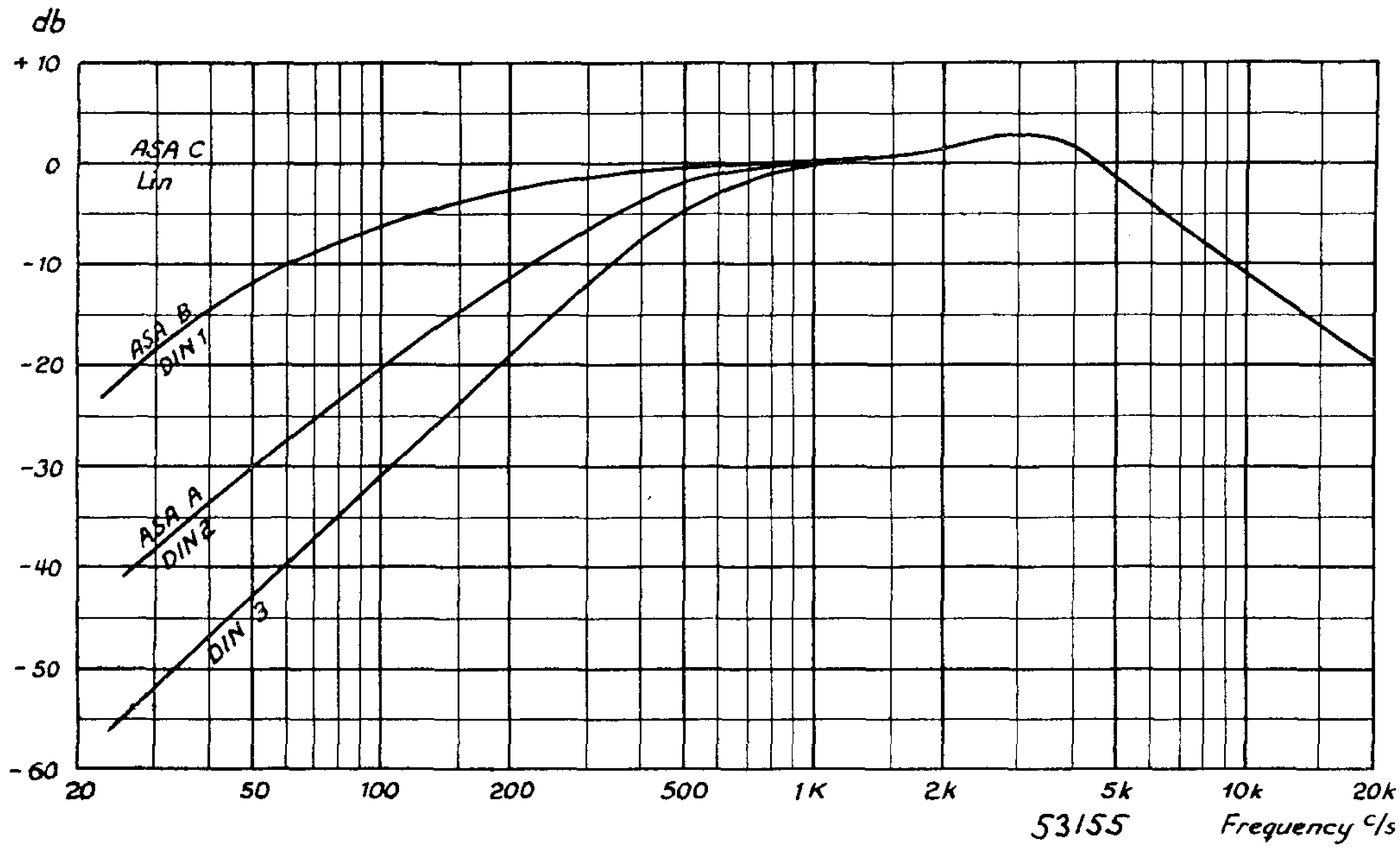

Fig. 9. The characteristics of the weighting networks.

on a special chassis, hung in rubber from the main chassis, and the tubes' filaments are fed with d. c. from a heater-rectifier. In this way it has been possible to achieve a hum-level on the grid of the input tube lower than 2 microvolts, and there is no disturbance from microphony in the amplifier even when measuring only a few microvolts.

The amplifier has two input jacks. The one is seven-poled and corresponds to the plug of a Condenser Microphone type 4111, whose built-in cathode-follower gets the necessary filament and anode current from the audio frequency spectrometer. The other input jack corresponds to a 14 mm coaxial plug and can either be coupled direct to the amplifier's input circuit or via a volume control, used for relative measurements, as one then can arrange for full deflection for any reference voltage. Switching between these two alternatives as well as between the two input jacks is carried out with the help of a three-position switch. The signal voltage is then lead from the input switch to a voltage-divider with five steps of 20 db and with a total impedance of 2.2 megohms. This switch, marked "Meter Range" on the front plate, serves to adjust the apparatus' sensitivity, and the value for full deflection on the meter can be varied from 10 mV to 1000 V. The switch has a further position marked "Ref." which serves to check the apparatus' sensitivity, a voltage stabilized with the help of a voltage regulator tube being applied to the grid of the input amplifier, in this position.

After the filter, whose characteristics are described above, there follows an amplifier which, in the same way as the input amplifier, has two steps and is supplied with negative feed-back, whereby the apparatus' sensitivity can be adjusted, the reference voltage being used as control.

By means of a toggle switch the amplifier's output circuit can be connected either to the built-in rectifier instrument or to a coaxial jack marked "Re-

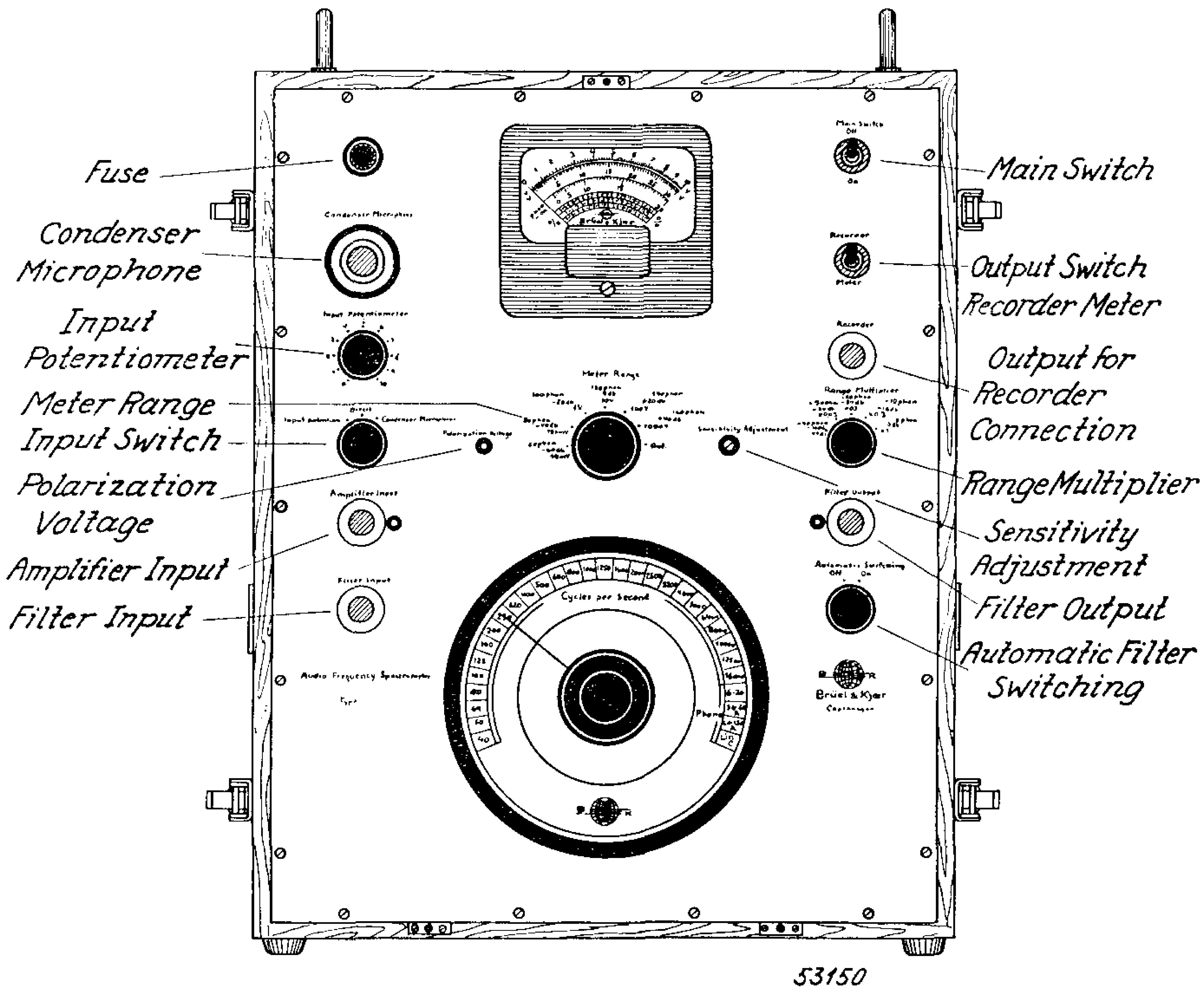

Fig. 10. Drawing of the Spectrometer 2109.

corder", serving for example either as connection to a head-phones, oscillograph or level recorder. The output impedance on this coaxial jack is approx. 2 kohms, and a maximum voltage of approx. 30 V is available. The built-in meter has a full deflection for approx. 10 V. It is graduated 0—10 and 0—3.15, and also has a scale of 0 to 20 db. There is also a set of scales permitting a direct reading of absorption coefficients when using Standing Wave Apparatus type 4002.

Between the filter and the output amplifier there is inserted a voltage divider with 4 steps of 10 db. This switch is marked "Range Multiplier" on the front plate. As the meter, as mentioned, has a full deflection for 10 V, and the filter voltage is normally approx. 1 V, there is only need for an amplification of 10 times in the output amplifier. The total amplification of the output amplifier is 1000 times, therefore normally only $1/100$ of the voltage from the filter is used. When the "Range Multiplier" switch is in the position corresponding to this, indicated by "$\times$ 1", one has full deflection on the meter for that value given on the "Meter Range" switch. By using the full amplification of the output amplifier, full deflection is obtained on the meter for 100 microvolts.

The power supply section of the apparatus contains three rectifiers. The one supplies filament current to the amplifier tubes, the next supplies filament current to the cathode-follower in a Condenser Microphone type 4111 if this is coupled on, while the third supplies anode voltage to the amplifier tubes and the cathode-follower, and the polarization voltage for the microphone cartridge. The anode voltage is stabilized with the aid of two glow tubes, and the polarization voltage to the microphone cartridge can be measured at a jack on the front plate of the apparatus marked "Polarization Voltage". The

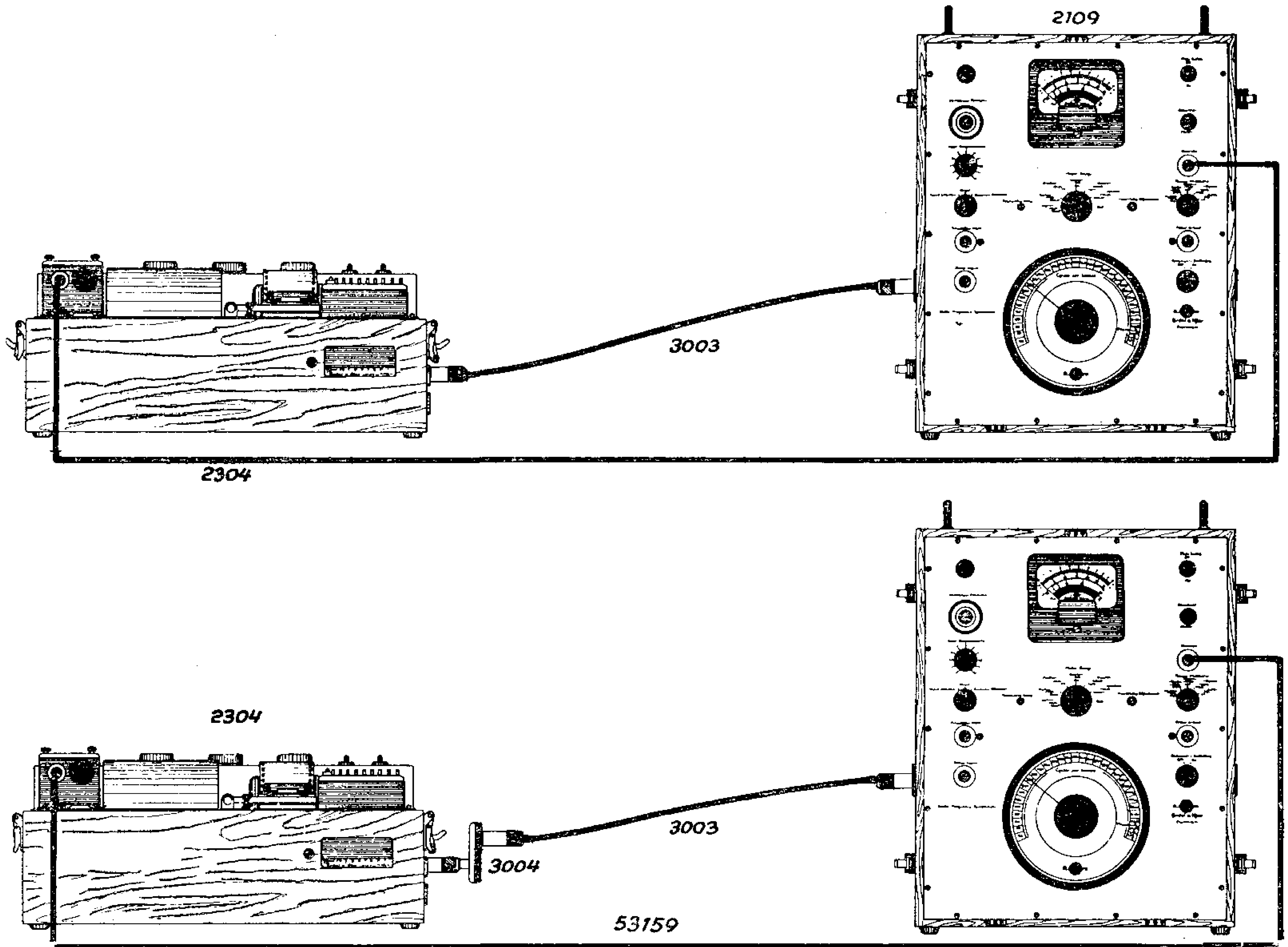

Fig. 11. Connection of spectrometer 2109 to Level Recorder 2304 with and without Speed Multiplier 3004.

apparatus can be operated from the a. c. supply with voltages of 115 - 127 - 150 or 220 V, and with 50 or 60 cycles per second. The consumption is approx. 30 watts.

In order to make full use of the advantage of the spectrometer, which is to have all 30 filters coupled in parallel directly following the pre-amplifier and switch the filter's output, the spectrometer should be coupled together with a Level Recorder, so that any one filter can be recorded in a predetermined time interval, measuring from a fraction of second to more than one hour.

Spectrometer 2109 is constructed for very convenient coupling to High Speed Level Recorder 2304. As is shown in the drawing of fig. 11 a flexible shaft type 3003 is attached either to the left hand or right hand side of the spectrometer, the other end of the shaft being attached to the Level Recorder's gear-box. It is indifferent which of the two terminals on the gear-box is used. The speed with which it is desired to traverse the spectrograms is adjusted with the help of the shift pinion in the gear-box. The output is then connected to each individual filter, driving the Spectrometer with the aid of wheels A to I in the Level Recorder gear box, for respectively 0.48—1.6—4.8—16—48—160—480—1600 and 4800 sec. Once this traversing speed has been chosen, the paper speed can be selected as desired. In this way frequency scales varying from less than a millimeter to several metres in length between the frequencies of 40 and 16000 c/s are obtainable. Paper with preprinted scales as shown in fig. 14 is

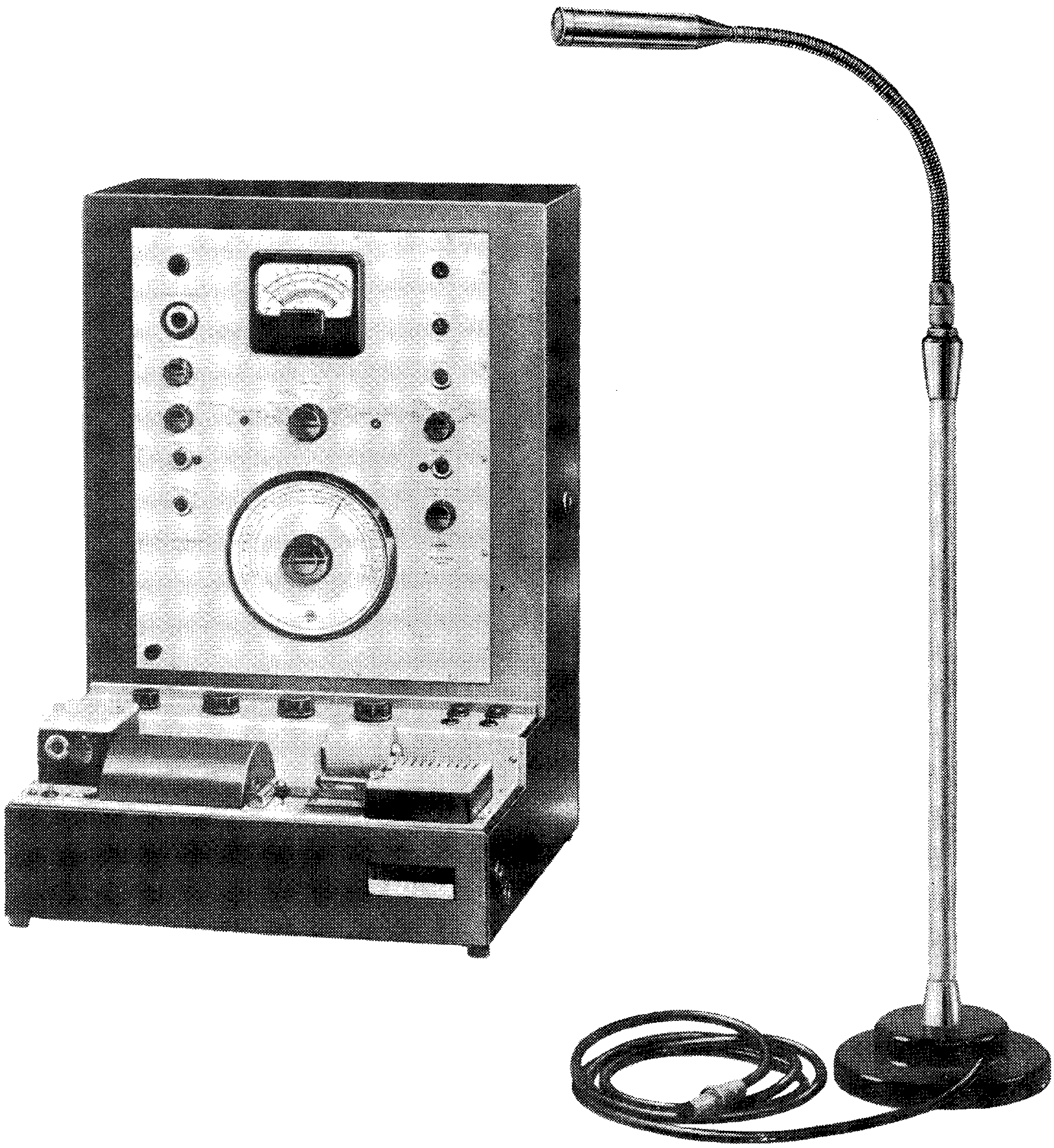

Fig. 12. Photo of Audio Frequency Spectrum Recorder 2311.

also available. Using this paper the paper speed can of course not be freely chosen any longer.

Instead of using two separate pieces of apparatus for these automatic recordings, the Audio Frequency Spectrum Recorder type 2311, as shown in fig. 12, can be used.

This apparatus consists of the Audio Frequency Spectrometer type 2109 and the High Speed Level Recorder type 2304 mounted together in a 19″ rack. The Level Recorder and the Spectrometer are connected by means of a chain drive, making possible the automatic recording of the sound analyses and acoustic noise, or a complex voltage. For this set-up Microphone 4111 in Stand 4112

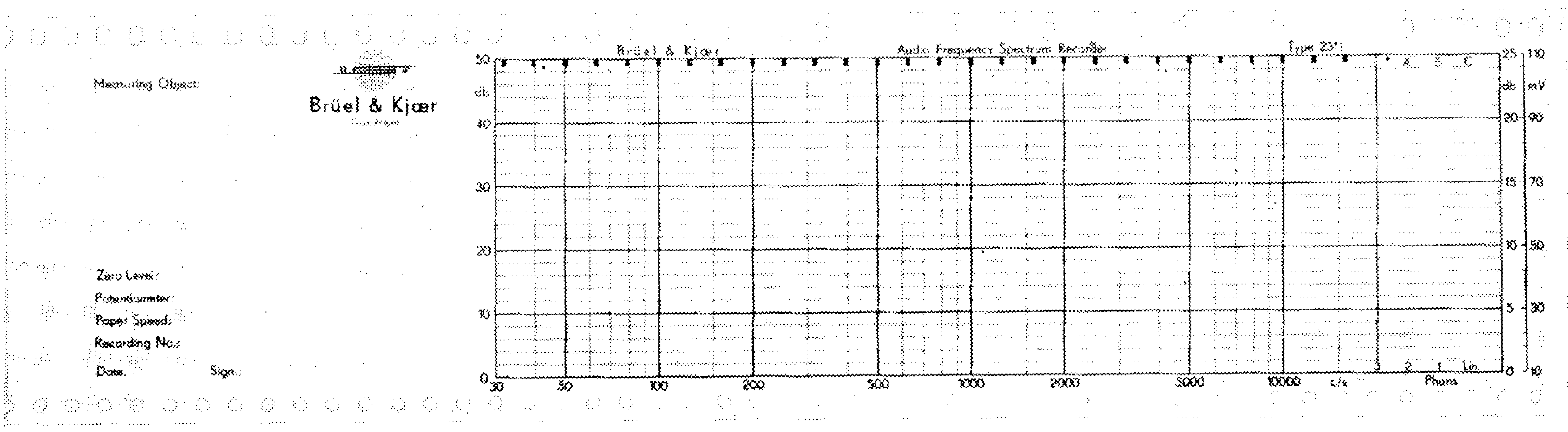

Fig. 13. One of the three different types of recording paper for 2311 with preprinted frequency diagram.

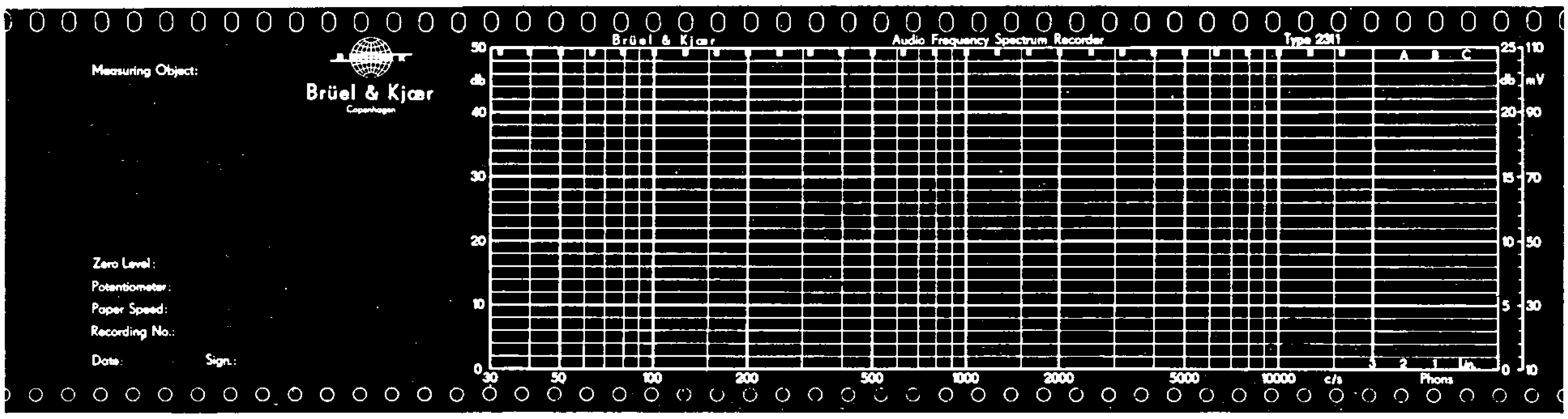

Fig. 14. Black film with transparent frequency diagram, for copying transparent recording paper type 3603.

is as a rule used, coupled direct to the Spectrometer with the 10 metre long cable. The above mentioned pre-printed paper is here used without inserting the Speed Multiplier mentioned, because the chain-drive is constructed to give the proper speed conversion. The recording paper with printed frequency diagram is supplied in three different paper types, one of which is illustrated in fig. 13.

Type 3601 is white paper intended for ink recording. Type 3602 is black paper coated with white wax, in which the record is scratched with the sapphire stylus. Type 3603 is transparent paper coated with red wax. This paper is specially suited for blue prints, and with an ordinary oxalid paper or photostatic copy paper gives a very contrasty reproduction. The diagram is here printed in black on top of the red wax layer. The curves scratched by the sapphire point will be transparent, as both the red wax and the plack printing will be removed by the sapphire stylus. When one wishes to make copies of the curves, only the scratched curves will appear on the copy, the original being transparent only here. Thus the frequency diagram itself will not appear on the copy. If it is desired to have the frequency diagram also printed on the copy, a double copying must be carried out, using a special diagram-negative, shown in fig. 14 and consisting of a black film on which the frequency diagram appears as transparent lines. With this procedure, both recording strip and film are fastened with scotch tape on a glass case illuminated underneath. The strip and film are placed each on one side of the photographic paper, onto which they can be turned for the respective exposures. Before inserting the paper, the film and recording strip are accurately synchronized by placing them over each other and adjusting them so that the frequency lines coincide on both.

Applications.

Measuring Electrical Voltages.

The different applications can always be reduced either to a measurement of an electrical voltage or an analysis of audio frequency voltages. In the first case the apparatus is used as a linear tube-voltmeter in the audio frequency range, with a maximum sensitivity of 100 μV full deflection. The input resistance of the instrument is 2.2 MΩ, and the input capacity approx. 20 pF. The frequency switch is set to the linear curve, and the desired voltage range chosen with the help of the switch marked "Meter Range", if necessary in connection with "Range Multiplier", the "Range Multiplier" switch being set to the least possible sensitivity and the "Meter Range" switch to a sensitivity giving full deflection. This is in consideration of the ratio between signal and noise as previously described.

If a direct reading of voltage is desired, the meter switch is set to "Meter". The meter satisfies the dynamic requirements set out in DIN 5045, and is therefore relatively quick, so that it is also well suited for indicating relatively short-lasting impulses. The meter measures the average value of the voltage, but the scale is calibrated in effective values for a sine wave voltage. The output amplifier can give a voltage which is 10 db greater than corresponds to full deflection for the meter. In this way a correct addition has also been assured for voltages of an impulse character.

If it is desired to record the voltages measured on a level recorder, for example type 2304, this should be coupled to the output jack marked "Recorder". With full deflection on the meter a voltage of 10 V is provided here, and as mentioned the amplifier is able to give a further 10 db higher voltage, i. e. approx. 30 V. The output impedance is approx. 2 kohms, and as a consequence is small in comparison with the level recorder's approx. 25 kohms input.

Analysis of Audio-Frequency Voltages.

Using the reference voltage as a control, absolute recording are possible by adjusting the 40 db line on the recording paper — in the case where a 50 db potentiometer is used — to correspond to full scale deflection on the meter, for any switching combination. The 40 db line corresponds then to the values read-off from the Meter Range and Range Multiplier switches, while a permitted overshoot of 10 db can be recorded too.

When carrying out a voltage analyses, it should be checked that the apparatus' amplifier is not overloaded. For this purpose, the frequency switch is first set on "Linear" and the voltage measured as described above. If then one or more of the different components of the investigated voltage should turn out to give no obvious deflection on the meter, the amplification is increased with the Range Multiplier switch. If "Meter Range" is employed, one is sure to produce undesirable distortion and combination tones due to the overload.

With the Spectrometer type 2109 it is not possible to carry out so fine frequency analyses as with a continuously variable analyzer such as type 2105. On the other hand the very powerful damping of frequencies outside the pass band is particularly valuable. The frequencies of the different partials are often known, in which case an exact analysis can be carried out by measuring the voltages. An example is shown in fig. 15 the analysis of the voltage in a power line. The fundamental here is 50 c/s, and all the harmonics must be whole multiples of this frequency. In this way it is possible, as shown, to record a spectrogram in which the mutual magnitudes of the harmonics are precisely given. If the distance between the harmonics is of the same order of magnitude as the bandwidth of the spectrometer, it is naturally impossible to separate the different harmonics from each other. For example, it is difficult to discriminate the 6th and 7th harmonics from each other.

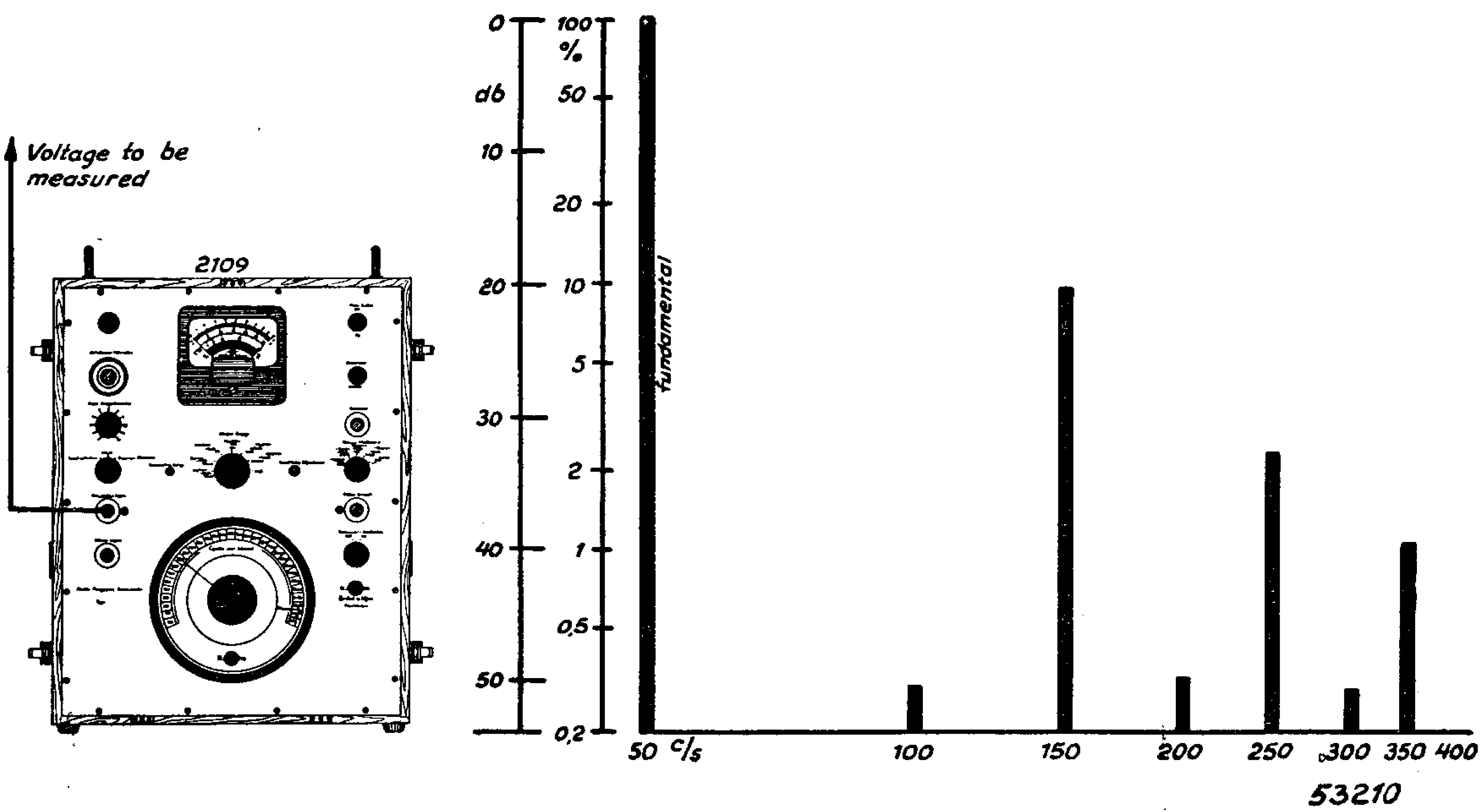

Fig. 15. Example of analysis of a power line.

If it is required to analyze a fundamental and a small number of harmonics, it may be convenient to have the harmonics measured as a percentage of the amplitude of the fundamental. For this purpose the instrument should first be tuned to the fundamental frequency, and a maximum deflection produced on the meter, the input switch being set to "volume control", and the amount of deflection adjusted with the volume control. The instrument should now be switched to the different harmonics, whereupon the percentages can be read on the meter scale. The ranges of 0—30 %, and 0—10 % are obtained by increasing the amplification by 10 and 20 db with the "range multiplier" switch.

Distortion Measurements on Nearly Pure Tones.

If it is wished to measure distortion-factors and furthermore analyze the lower harmonics of nearly pure a. c. voltages such as the output from a high-quality oscillator, it may be that the spectrometer's selectivity will not go as far as this. The spectrometer can then be used in connection with the Blocking Network type 1602, as shown in fig. 16.

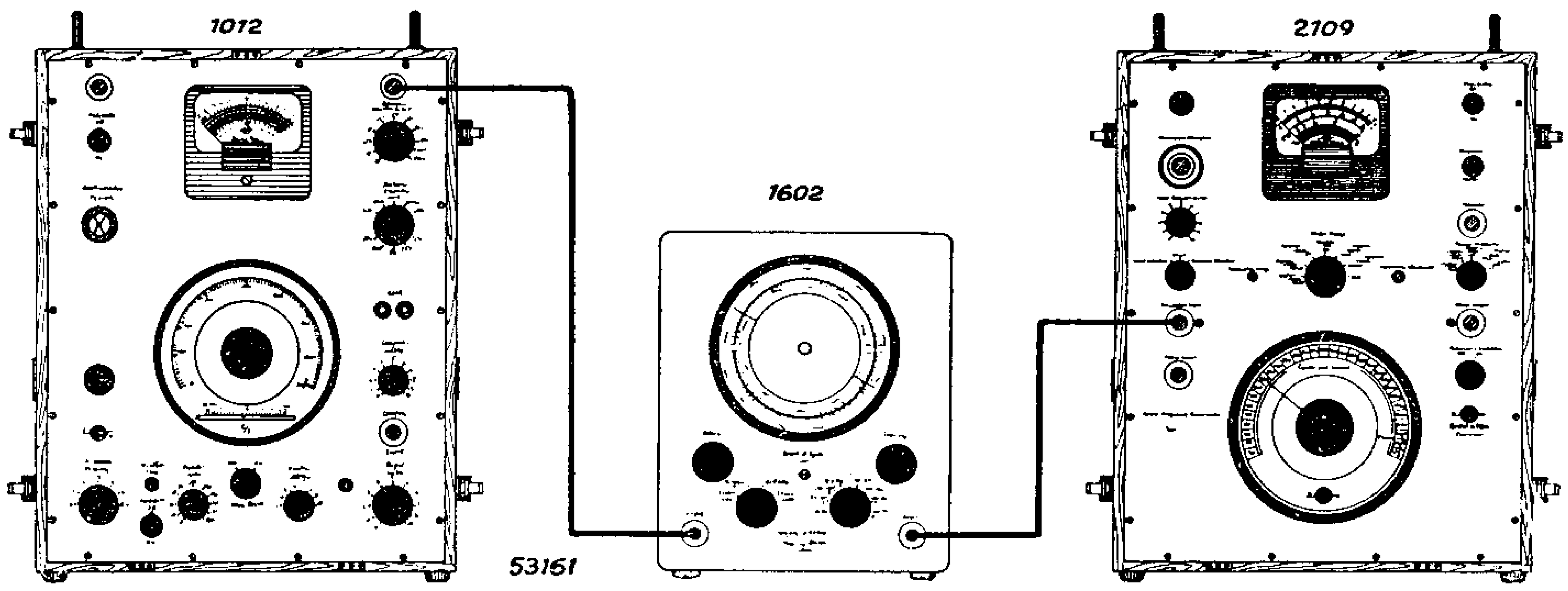

Fig. 16. Distortion measurements of nearly pure tones by using the Blocking Network type 1601.

The Blocking Network 1602 is adjusted to damp a single frequency very strongly, while allowing all the other frequencies to pass through the filter. Measurements are made by first setting filter 1602 to its linear range, then adjusting the spectrometer's sensitivity so as to give full deflection for the frequency in question. The spectrometer can then either be switched to its linear range, or selectively tuned to the fundamental frequency. The filter is then tuned so that the deflection on the analyzer becomes minimum, i. e. the basic frequency is completely damped out. Analysis of the harmonics can then be undertaken in the normal way, and in practice it is possible to measure distortion components right down to 0.01 %. In this case even the "meter range" switch can be used to increase the amplification. To obtain the correct amplitude relation with requencies with lie below the fundamental frequency, for example various hum components, filter 1602's frequency characteristic must be used for correction. The correction of frequencies which lie above the fundamental frequency is not necessary. The total distortion can be calculated by adding the effect of the various components, but it can also be obtained direct as a minimum deflection on the spectrometer when set to the linear response after the filter has been adjusted to give minimum.

Measurement of Sound Pressure with Condenser Microphone Type 4111.

As said before, the Spectrometer is designed primarily for acoustic analyses.

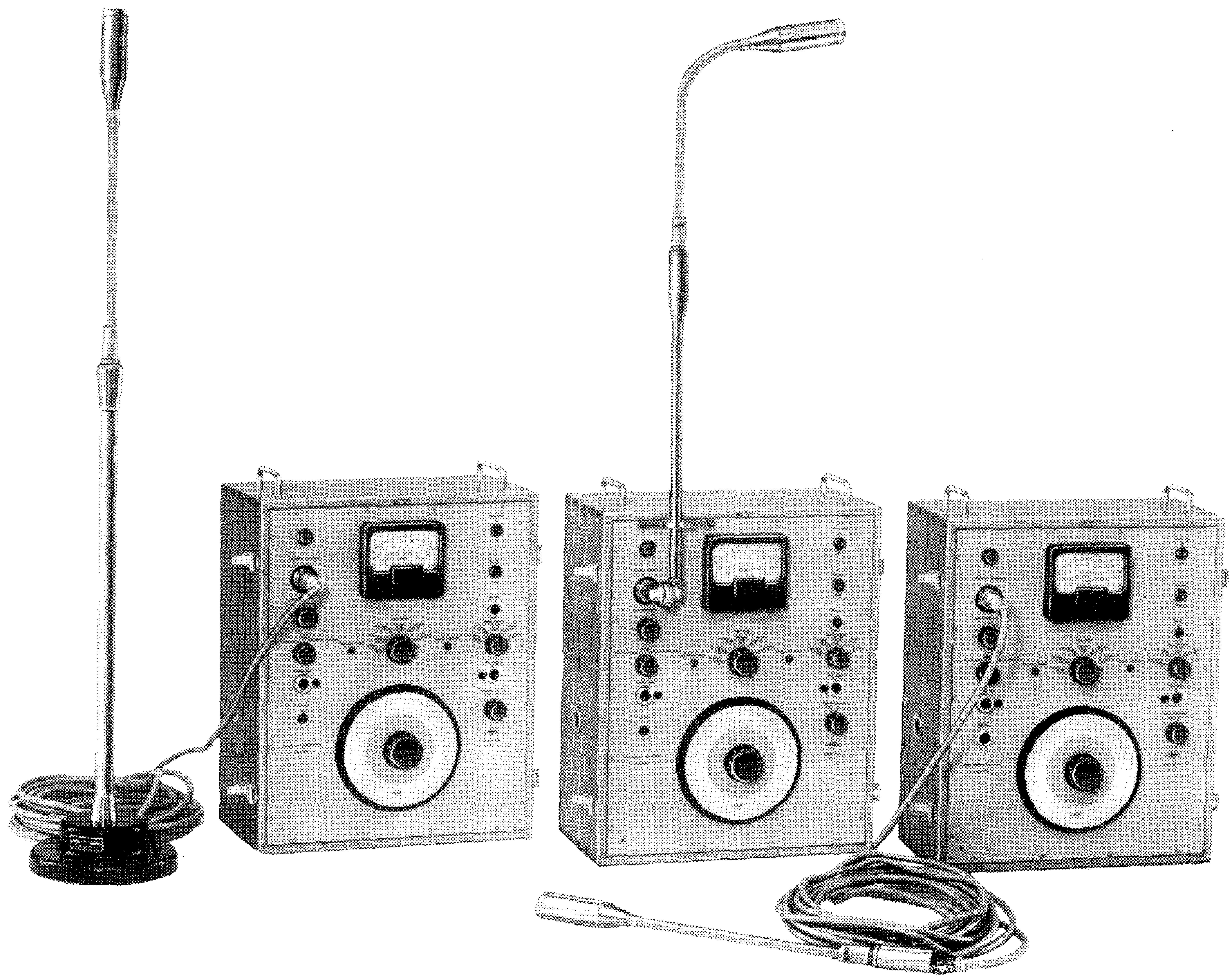

Fig. 17. Photo of the Condenser Microphone Type 4111 connected to the Spectrometer. Left: Floor Stand Type 4112, Middle: Extension Rod Type 4115, Right: Extension Cable 4114.

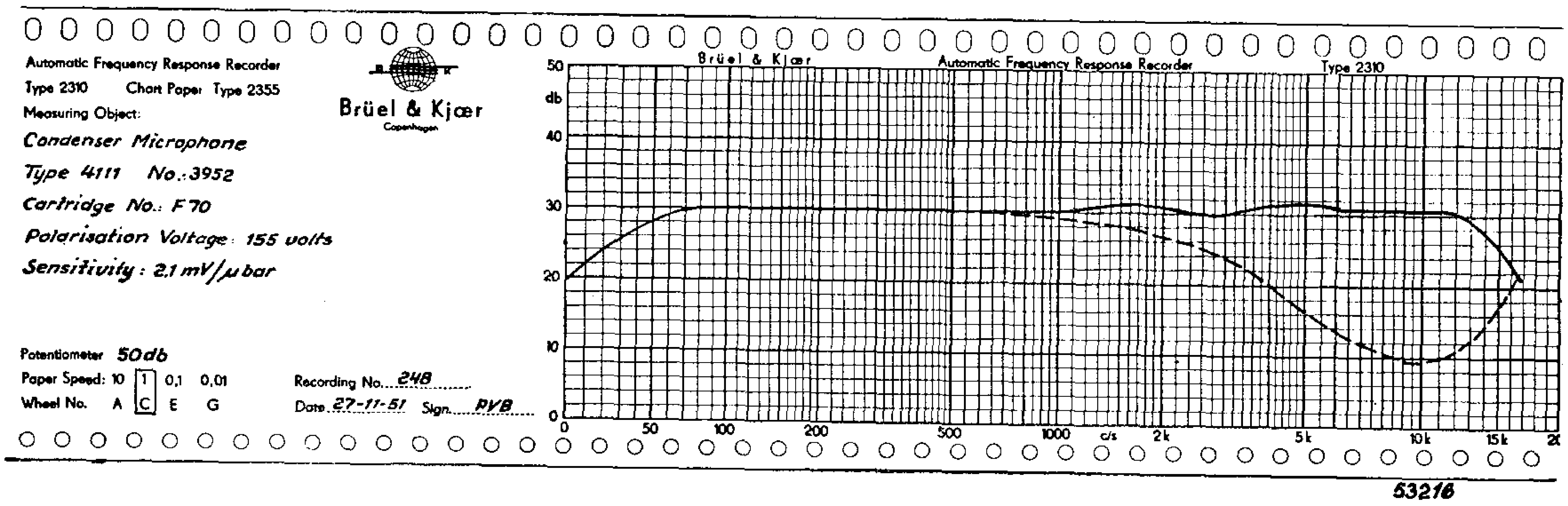

Fig. 18. Frequency response and absolute sensitivity for Condenser Microphone Type 4111.

In most applications Condenser Microphone type 4111 is used. It can be connected to the 8-poled screened jack on the Spectrometer's front plate either by inserting the microphone plug direct in the jack or by using an intermediate unit in the form of Floor Stand type 4112, Extension Cable 4114 or Extension Rod 4115 supported by part 4116. In fig. 17 some of the possible connections are shown. The sensitivity of the Condenser Microphone, expressed in mV/μbar for a definite specified polarization voltage, follows with each instrument as

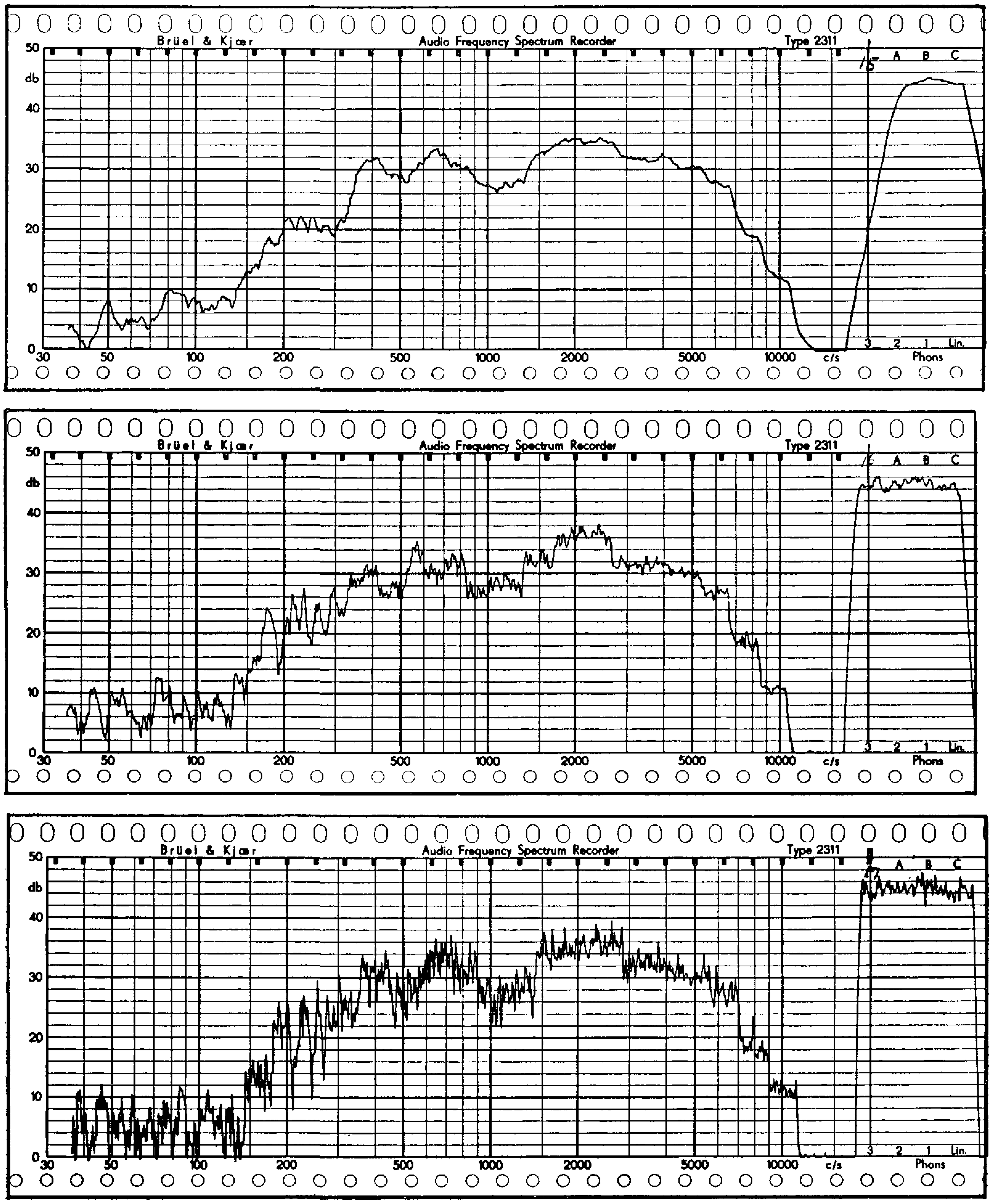

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Fig. 19. Spectrogram of noise from a lathe, taken with three different writing speeds: 50, 200 and 700 db/sec. The 50 db potentiometer is used. Zero level: $2 \cdot 10^{-2}$ μbar.

an individual calibration for the particular microphone in question. Fig. 18 shows such a curve, showing the free field calibration of the microphone. Both the instrument's serial No. and the cartridge serial No. are given on the curve. The sensitivity given corresponds to the output voltage after the built-in cathode follower in the microphone.

If the microphone is attached to a spectrometer whose polarization is different to that with which the microphone has been measured, a correction for the difference in polarization voltage must be made, the sensitivity being directly proportional to the polarization voltage.

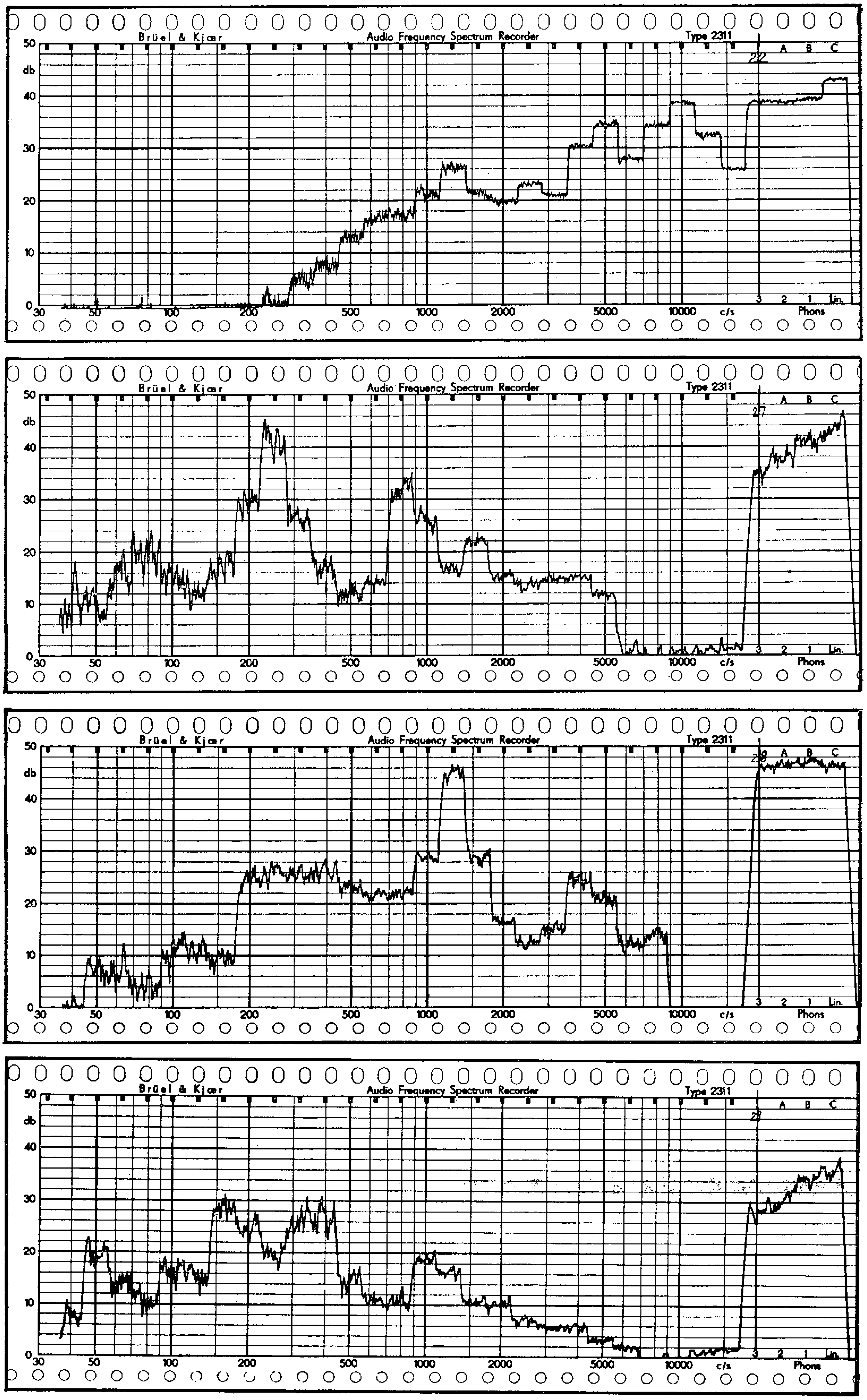

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Fig. 20. Spectrogram of

1) Air streaming from piping. Zero level: $6 \cdot 10^{-2}$ μbar.
2) Electric motor on stamping machine. Zero level: 10^{-2} μbar.
3) Motor for small drilling machine. Zero level: 10^{-2} μbar.
4) Motor for large drilling machine. Zero level: 10^{-2} μbar.
All recorded with 50 db potentiometer.

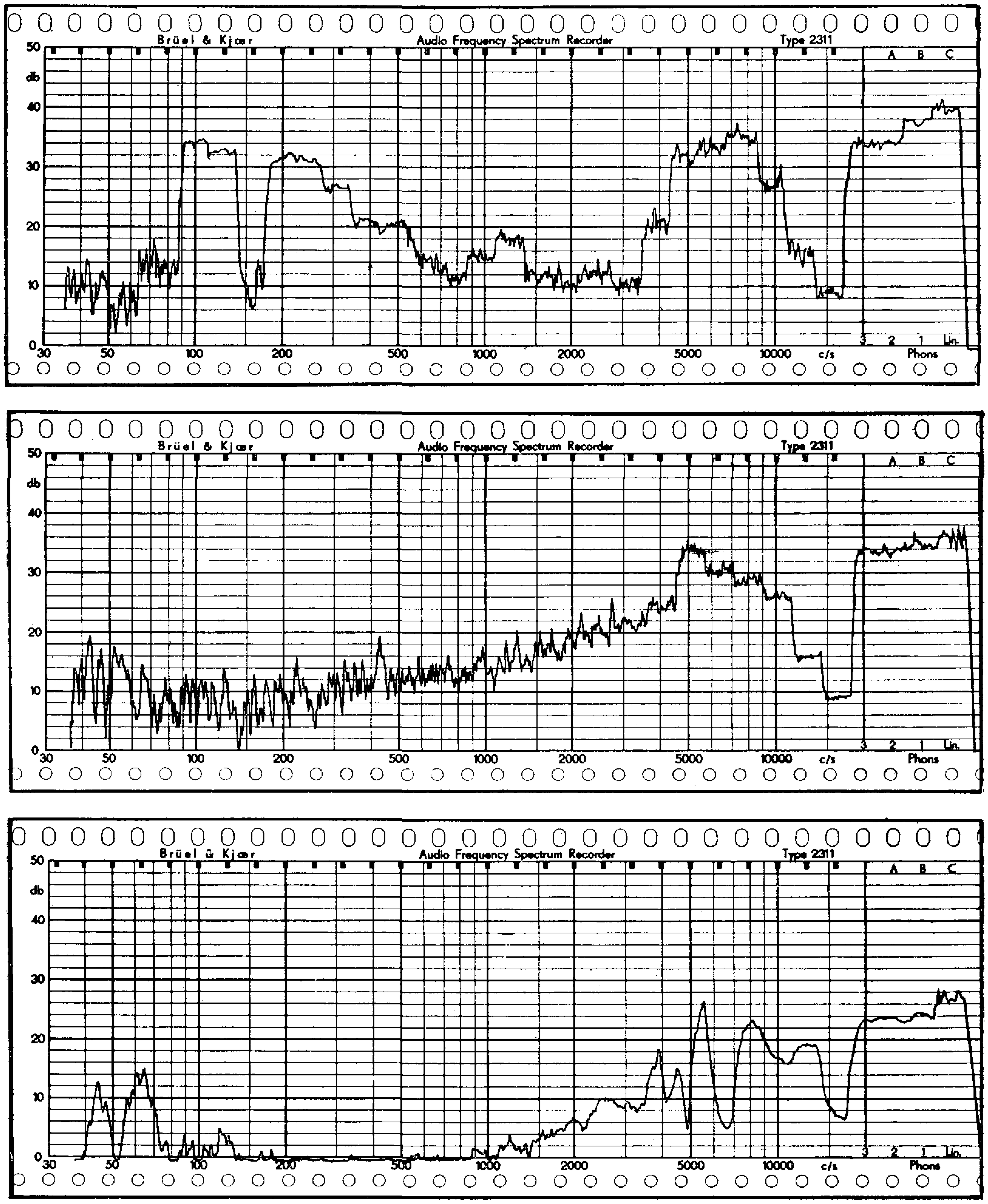

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Fig. 22. Spectrogram of speech sounds:
1) a as in father.
2) z as in zero.
3) s as in Mississippi.
Zero level 10^{-2} μbar.

When the Spectrometer's voltage sensitivity is adjusted, the measurements can begin. If pure tones are being measured, for example, those from a loudspeaker driven by a beat-frequency oscillator, the linear frequency characteristic can be used, and the voltage indicated as a function of the frequency read off and noted. If the sound pressure being measured is very small, so that undesired noise disturbe the measurement, it is recommended that the selective ranges on the Spectrometer be used.

Spectrograms.

The Spectrometer's most important use is the recording of acoustic spectrograms of different sounds in conjunction with Condenser Microphone 4111. With Condenser Microphone 4111 and the Audio Frequency Spectrometer alone, the sound pressure in each band must be read off on the Spectrometer's instrument. These values as read off must then be recorded in a frequency spectrum so as to facilitate a comprehensive picture. With the combination of Microphone 4111 and Audio Frequency Spectrum Recorder 2311, the spectrograms are directly recorded, and on the following figures a series of characteristic examples is shown.

Fig. 19 shows the spectrogram of noise from a lathe. The three different curves are recorded with different writing speeds on the recorder. The curve is smoothed out considerably with low writing speed on the level recorder, and with high writing speed all the small variations in the sound become very pronounced. Note the fact that the irregularities with sound which is recorded with a linear characteristic are considerably lesser than the irregularities in the single band, and that the irregularities in the single band are greatest for the lower frequencies and least for the higher frequencies, quite in accordance with the general statistical theory for the reflection of sound waves in enclosed spaces. Fig. 20 above shows the characteristic spectrum for air streaming from a system of pipes. It will be seen that this noise consists almost entirely of high frequencies. The three next spectrograms are all taken on electric motors, and it will be seen how varied the spectrograms are.

Fig. 21 shows different characteristic sounds, above a double toned automobile horn, in the middle the sound from an ordinary wrist-watch taken at a distance of approx. 20 ins. Note the very weak zero level. The Spectrum Recorder has been working here just at the limit of its own noise level, at the lowst level it is possible to analyse. The lowest diagram shows an alarm clock ringing. (see inside cover.)

Fig. 22 shows the spectrogram from some characteristic speech sounds. These spectrograms are taken with the highest speed of the recording paper, and as a result of this with a very great writing speed on the level recorder. The zero level given on the figure, expressed in μbar, refers to the db scale to the left on all the spectograms, which means that it is possible to read off direct the sound pressure in db above the given zero level within each frequency band.

Our next issue of Technical Review will describe some other applications of the Audio Frequency Spectrometer and Automatic Spectrum Recorder, among which will be some quite new measuring methods, such as the **automatic recording of harmonics** *in both electrical and acoustical equipment and a loop method for* **recording transients** *and visualizing 3-dimensional speech spectrograms.*

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