AN EARLY APPLICATION OF DECIMETRE WAVES TO COMMUNICATION BETWEEN SHIPS

by

E. C. S. MEGAW

Admiralty Signal Establishment

and

W. E. WILLSHAW

Research Laboratories of the General Electric Co. Ltd., Wembley, England.

1. – Introduction.

At the end of 1936 the Research Laboratories of the General Electric Company undertook for the Admiralty a programme of research and development to advance the techniques and to explore certain possible naval applications of wavelengths below 60 cm. Although laboratory studies and some field work had been carried out on much shorter wavelengths during the previous decade, it was considered that this figure represented the limit up to which well-established techniques, using negative grid triodes, could then be applied to practical radio problems. The initial terms of reference were wide and in fact covered the whole problem of the generation, measurement, transmission, and reception of these very short wavelengths, down to whatever limits might be considered technically feasible or practically useful.

In order to narrow down this wide field sufficiently to produce practical results in a reasonable time, it was divided into two broad objectives:

1. to develop the techniques required for practical communication systems in the region of 50 cm, which was considered suitable for omni-directional applications; and
2. to continue the study of methods of transmission and reception for wavelengths in the region of 10 to 30 cm, which were

particularly attractive for highly directional working, but for which more fundamental development was still required.

After some months of preliminary work, in the course of which several demonstrations of telegraph and telephone communication with laboratory equipment were given, and the installation requirements in H. M. ships for both highly directional and omni-directional equipment were explored, it was decided to proceed with the development of equipment operating in the 50 cm region for sea trials, with the aim of meeting a specific naval requirement. The present paper gives an outline of this development and of the characteristics of the equipment which resulted. A return to the second objective was made in 1939, when technical proposals were prepared for a naval communication system to operate on a wavelength below 10 cm; this, however, was not proceeded with since later work showed that the propagation characteristics of these wavelengths were not consistent with the operational requirements.

2. – General requirements and choice of techniques.

The equipment described in this paper was required for ship-to-ship communication over short distances, primarily for manoeuvering purposes. A normal maximum range of about 10 miles (18 km) was originally specified; this was revised, considerably later, to 3 miles (5.5 km) certain communication in any direction. It was essential to reliability, particularly for communication with a number of ships simultaneously, that a high order of stability should be provided. The possibility of working over a wide frequency range was also required. Initially 2 or 3 channels would be required to operate without mutual interference in the same area, this number increasing eventually to 20 or 30. Telegraphic communication at hand speed was specified, with the possibility that voice communication might be required later. The advantages sought by using very short radio waves in place of existing visual means of communication were secrecy and fog-penetration.

It was considered that the use of decimetre waves would offer a substantial increase in security, as well as much better prospects of obtaining good omni-directional characteristics (which had proved difficult with metre wave naval equipment), without requiring excessively large transmitter power. It was also considered that the other requirements could be met on these wavelengths without a long period of research and development.

The magnetron was chosen as the only available source of sufficient power in the selected wavelength range of 40–60 cm. Some study had already been made of methods of frequency stabilization, which were considered promising. The super-regenerative type of receiver, combining good sensitivity with simplicity, was preferred to the superheterodyne with the relatively poor mixers then available in this waveband. The aim was to use separate single omni-directional aerials for transmission and reception, mounted at the greatest height available in the ship, rather than multiple aerials covering separate sectors mounted lower. It was considered feasible to use cables to connect the equipment to the aerials. By this means it was intended to obtain a much greater freedom of choice of positions both for aerials and equipment than would have been possible, if the practice, which was then current even for metre wavelengths, of mounting H. F. equipment close to the aerials with short open transmission lines, had been followed. It followed that aerials must be developed, which would operate satisfactorily without adjustment over the required waveband.

In general the aim was to produce equipment, which would be fully comparable in ease and stability of operation with naval equipment then in use in the H. F. band, and which would be capable of integration with the existing organization of naval communications equipment.

3. – Experimental studies and development work.

3. 1. TRANSMITTER.

3. 1. 1. *Choice of transmitter valve.*

Investigations were carried out initially with an existing design of 4-segment magnetron having an anode diameter of 10 mm and a pure tungsten cathode of 0.17 mm diameter. This was fitted experimentally with a 2-wire grid for modulation by space-charge control. The valve was connected to a 2-wire line circuit having an effective length of $3\lambda/4$, alternate segments being connected to the same conductor of the circuit. It was found that, though satisfactory amplitude modulation, with very small frequency modulation, could be obtained with a suitable modulating circuit, the output obtainable was considerably lower than in the corresponding valve without a grid, and was of the order of a few watts mean at a wavelength of 60 cm. The standard valve without a grid, and with cathode eccentric, gave an output of the order of 20 W mean at the same wavelength, but required an inconveniently high voltage at a wavelength as low as 40 cm. Accordingly, in order to cover the wavelength range 40–60 cm, a 4-segment valve (Fig. 1) with reduced anode diameter (7 mm), and with a 0.25 mm thoriated tungsten filament giving greatly increased emission, was developed. This gave a similar output with much reduced variation over the required wavelength range, when operated with constant magnetic field strength.

After some initial experiments with magnet designs, a C-shaped permanent magnet (Alnico) was developed for this purpose by Messrs Darwins Ltd.; it gave a gap field strength in the equipment of about 900 oersteds.

During the course of the work measurements were made on these valves with a view to assessing their suitability for use in a communication system. In particular the stability of frequency with anode and cathode voltage, and circuit impedance, was studied and it was concluded that some form of frequency stabilization would be necessary, in order to satisfy the high standard set by the operational requirements. A stability of the order of a few parts in 10^4 was considered desirable, in order to guarantee the reception of a signal by any receiver within range, after it had been set for the same nominal frequency.

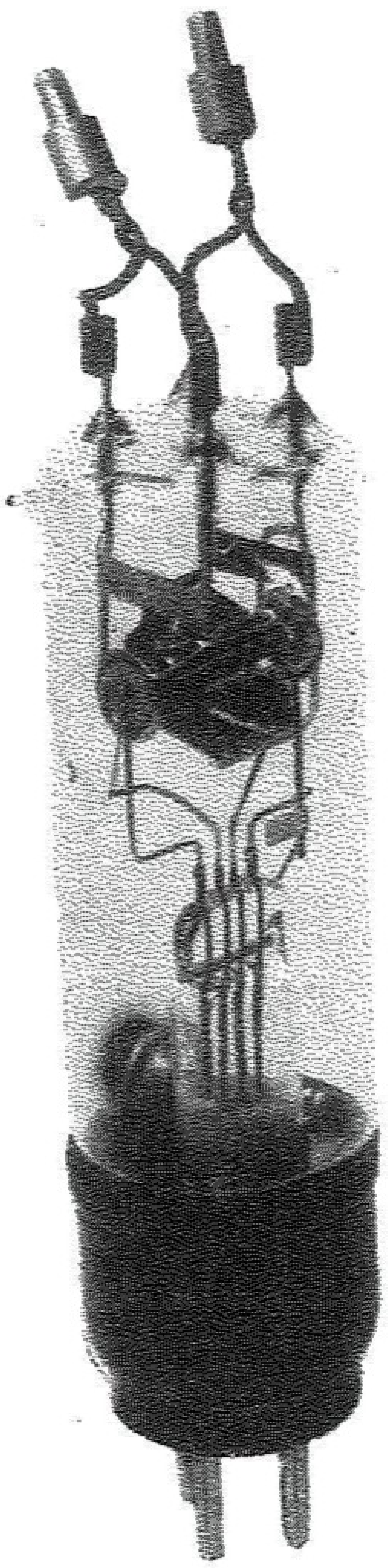


Fig. 1. – Transmitter magnetron.

Further measurements of anode modulation characteristics of the first type of valve (without grid) showed that, though amplitude modulation of good linearity could be obtained, with low modulation depth, it was preferable in the interests of power economy and general stability for modulation to be carried out by switching rapidly from an oscillating to a non-oscillating condition, i. e. by square-wave modulation. This meant that, with existing techniques, signalling was limited to telegraphy, effected by keying the interrupted power.

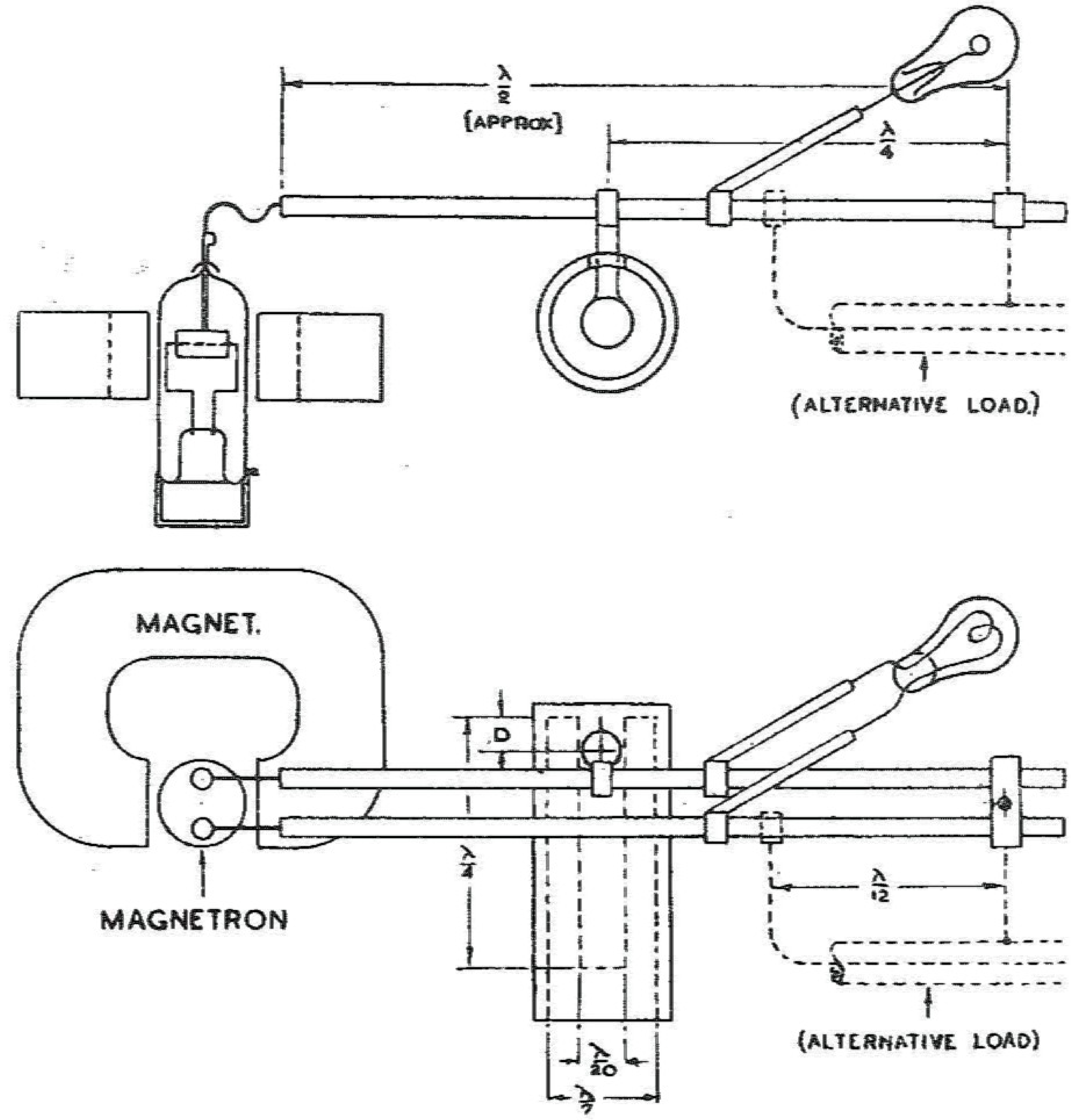


Fig. 2. – Frequency stabilization by means of concentric line resonator.

3. 1. 2. *Frequency stabilization.*

In order to achieve r. f. frequency stabilization, a number of experiments were made with "high-Q" circuits of different forms.

In the most promising of these a half-wave coaxial resonator was used. It was connected to the oscillator circuit near a voltage antinode by a short lead taken from its inner conductor near one of its closed ends. The resonator then provided a parallel tuned circuit connected effectively in parallel with the valve. This arrangement was immediately successful and, after changing to a quarter wave open-ended line resonator, an improvement of frequency stability of 10/1 was obtained with a power loss in the resonator of only 10 %. Fig. 2 shows the arrangement with approximate dimensions. Further work on the effect of changing resonator

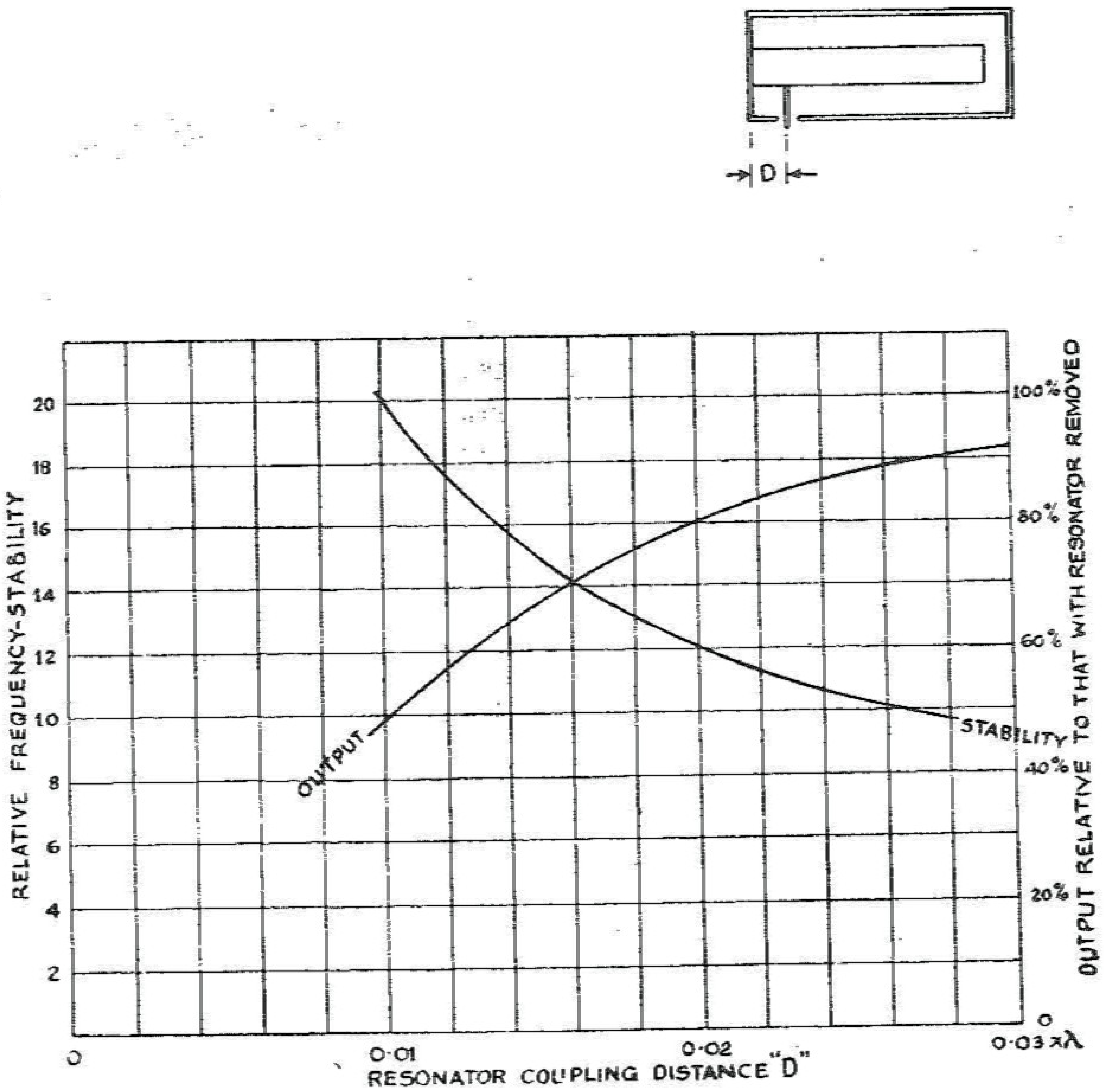


Fig. 3. – Relation between frequency stabilization, power output, and degree of resonator coupling (experimental resonator).

coupling parameters enabled a curve relating frequency stability and power output to resonator coupling to be obtained, and this is shown in Fig. 3. As expected, it was found that the valve circuit should be adjusted so that the frequency generated was approximately the same without resonator as with it, but small changes of frequency could be obtained by detuning the valve circuit. Further by varying the frequency of the resonator, for example by length variation, the stabilized frequency of the oscillator could be controlled over a wide range. In the final form of the resonator the diameter of the inner conductor was doubled over about one-third of its length at the closed end. This gave a higher Q-factor, and allowed the length of the connecting lead to the valve circuit to be reduced to a minimum. With this arrangement a stabilization factor of 20 or more was obtained with a power loss of about 1 db. Early experimental work on this system was carried out with a symmetrical lamp load. Replacement of this by a single coaxial cable of 70 ohm impedance, having its outer conductor attached to the shorting bridge of the line and its inner to one of the two conductors (shown dotted in Fig. 2), showed that operation was still quite satisfactory.

As an indication of the stability obtained, the frequency change resulting from a 5 % change in anode voltage was of the order of 0.2 Mc/s, and the total frequency change after switching on was — 0.05 Mc/s, when the stabilized frequency was 500 Mc/s.

3. 1. 3. *Modulation.*

As already described, it was decided to modulate by interruption of the carrier at audio frequency, telegraphic keying being carried out in initial experiments by changing the frequency of interruption, the receiver being made selectively responsive to the marking frequency. A marking frequency of 1000 c/s, and a spacing frequency of 3200 c/s were used. The main objective of this system was to avoid temperature changes, and consequent frequency changes, during keying. It was later shown that these changes were unimportant with on-off keying, and this was finally adopted, in order to permit "listening through" (i. e. reception in the intervals of keying).

3. 1. 4. *Voltage stabilization.*

In order to ensure stable modulation characteristics and constancy of frequency and power, the use of a stabilized anode voltage supply was investigated. Fig. 4 shows the basic arrangement used, and this proved very successful in operation. In principle the stabilizer consists of a series regulating valve, whose controlling potential is obtained through a d. c. amplifier from the difference between a suitable fraction of the output voltage and a stable reference voltage. Different stabilized output voltages may be obtained by altering this fraction. Modulation and keying may

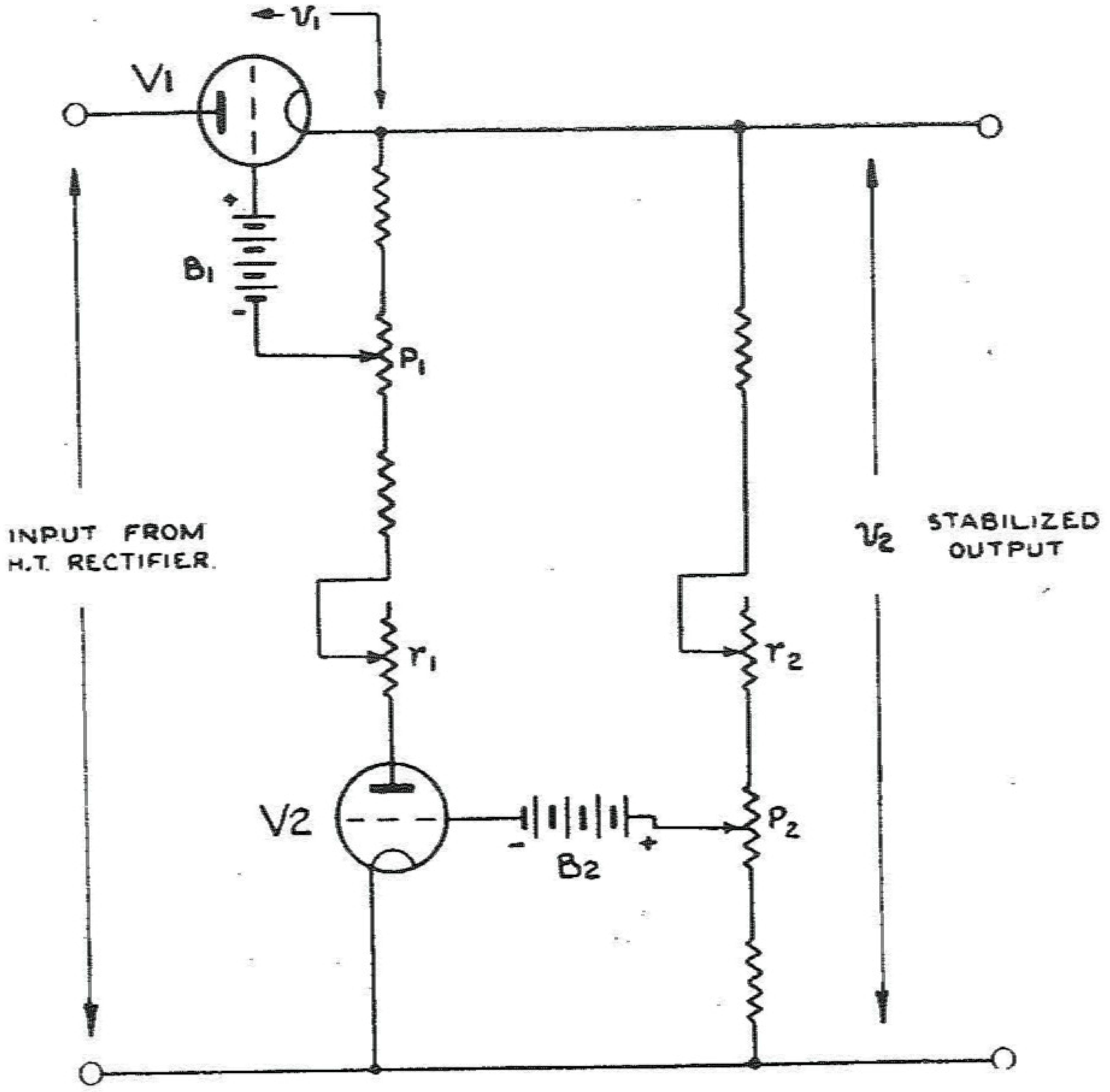


Fig. 4. – Basic circuit of voltage stabilizer.

be affected by changing the value of the reference voltage, the output voltage varying in sympathy. Gas-filled voltage stabilizers were used both for the reference voltage B_2 and the bias voltage B_1; preset controls P_1 and P_2 were incorporated to allow for the differences between the stabilizing voltages of different specimens of the gas-filled stabilizers. The present controls were adjusted by measuring both the grid voltage v_1 and the output voltage v_2. The voltage v_1 was indicated continuously to check that the correct voltage was being supplied to the input terminals t_1 t_2 from the high tension rectifier.

In order to change the stabilized output voltage, the resistances r_1 and r_2 could be varied together, r_2 changing the ratio between reference voltage and output voltage, and r_1 maintaining the current through valve V_2 constant, with the correct input from the high tension rectifier. By these means a stabilized anode voltage continuously variable between 600 and 1200 volts was provided. Mains voltage variations were reduced by a factor of about 30. For modulation, the reference voltage was varied at the modulation frequency by the use of a valve-resistance potentiometer, the valve being made alternately conducting and non-conducting by a sufficiently large sinusoidal voltage applied to its grid, so that the output voltage was consequently reduced from its stabilized value sufficiently to stop the magnetron oscillating. The mean reduction was about 190 volts. By use of a resistance switched in parallel with the valve, by a relay, the anode voltage could be held at the lower value so that on-off keying could be effected.

3. 2. RECEIVER.

In addition to the general considerations already mentioned, the decision to use a super-regenerative receiver for this application was influenced by two practical matters: the existence in small-scale production of the "acorn" triode, capable of oscillating under laboratory conditions up to a frequency of about 900 Mc/s; and the existence in the Laboratories of a heterodyne frequency meter which used this triode to cover the range 30 to 500 Mc/s, and which had been designed so that it could be used as a very compact super-regenerative receiver in this range. It was in fact so used for the first trials and demonstrations in the region of 500 Mc/s, covering distances of a few miles.

The first problem was to develop an oscillator circuit of good stability, electrical and mechanical, to cover the required frequency range with a high re-setting accuracy. Line circuits with sliding bridges were attractive for ease of reaching the highest frequency, but were abandoned because of the difficulty of design for sufficiently accurate and silent tuning. Among several unconventional arrangements tried, one, in which the inductance of a parallel strip line was varied by rotation of a suitably contoured copper block between the strips, was the most promising. A short length of line tuned by a symmetrical condenser, from the stator plates of which the acorn triode was mounted, was finally adopted as the best compromise. It covered 415 to 705 Mc/s in 8 steps, selected by changing the position of a present capacity bridge (see Fig. 5). Originally a tuned cathode line was used, but it was found that it could be replaced by chokes without serious increase in the anode current required for oscillation threshold, which varied between 1.5 and 7 mA over the frequency range quoted.

A quenching frequency of about 125 kc/s was generated by a triode oscillator which injected about 3 V by inductive coupling into the anode circuit of the acorn triode, in series with its audio output transformer. These were found to be flat optimum values for operation in the logarithmic mode; the quenching frequency could be increased to several Mc/s with little change. The optimum reaction setting was not excessively critical; the permissible anode voltage range was about 4 % for signal/noise output within 1 db of the optimum. A stabilized supply was provided. Stabilization of the detector heater supply was found unnecessary.

Input coupling arrangements to the super-regenerative detector were studied in some detail. To obtain optimum performance over the required frequency range, and to increase selectivity by preselection, a half-wave balanced line tuned by length variation was used. The aerial cable was coupled to this line by a direct tap, which it was found could be left fixed over the range 500 to 700 Mc/s, to one end of the tuned line; its other end had a fixed inductive coupling to the oscillator line. In addition to increased rejection of strong signals off tune (up to 30 db improvement), this arrangement provided a rough absorption frequency meter. These advantages were considered to outweigh the disadvantage of an extra control, particularly in a receiver which was not intended to be used for searching. The loaded Q of the pre-selector circuit was of the order of 300.

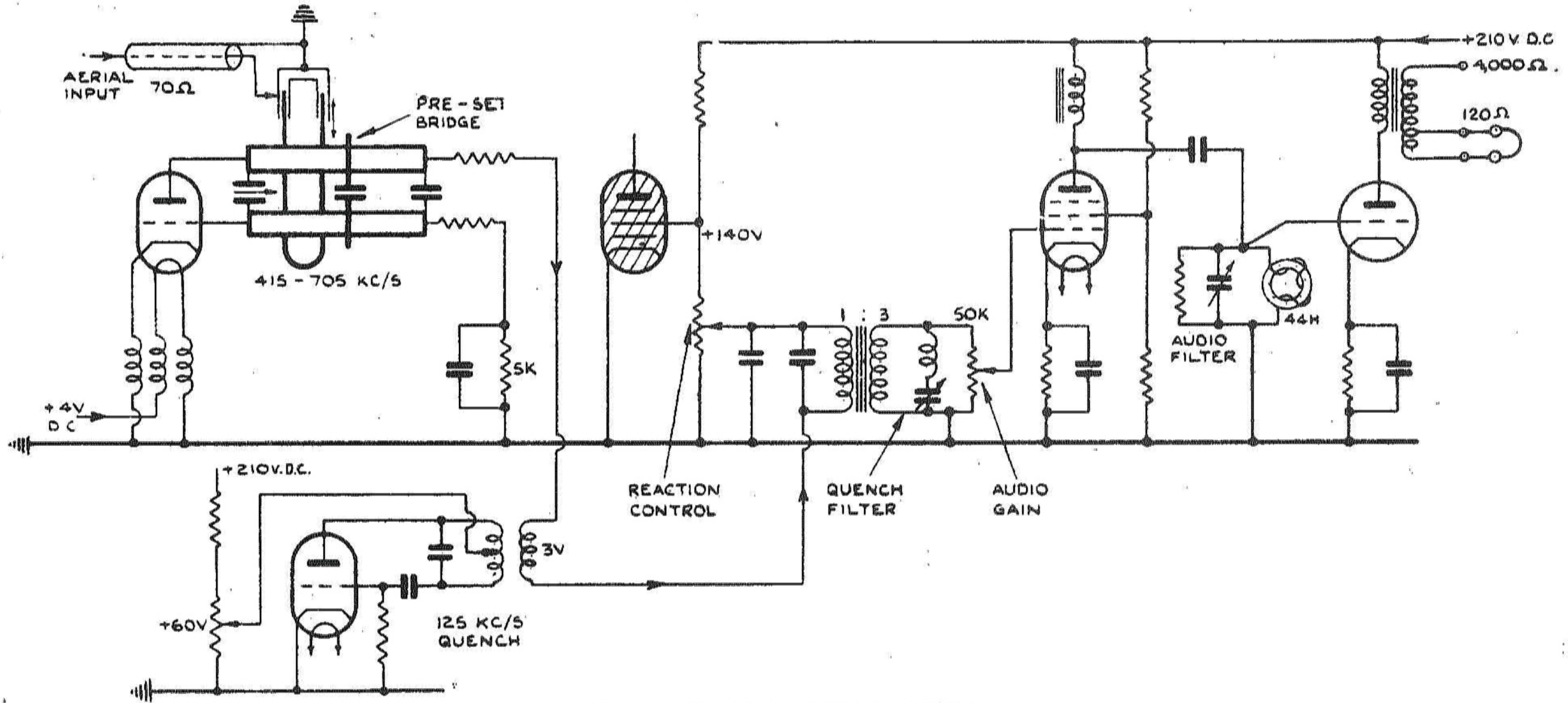


Fig. 5. – Simplified diagram of receiver.

The audio amplifier circuit is indicated in Fig. 5; a pentode amplifier and triode output stage were used, giving a gain at 1000 c/s of some 60 db between detector anode circuit and high impedance output, with input and output impedances both about 5000 ohms. An audio filter using a dust-core toroidal coil was introduced to improve the signal/noise ratio and to explore the possibility of using several alternative audio channels on one carrier by this simple means. The latter was not considered attractive, but the filter was retained for signal/noise improvement. With the input and output taken across 1/70 of the coil turns, a Q-factor of about 50 was obtained, but this had to be reduced by shunting to a value of about 10, to avoid objectionable ringing on 1000 c/s morse signals at up to 35 words per minute. A trimming control was provided on the filter tuning. It was something of a disappointment to find that the reduction in audio bandwidth from a few kc/s to under 100 c/s made no difference whatever to the weakest signal which could be heard in noise; the narrower the bandwidth the more similar signal and noise sounded; also no difference in signal/noise threshold could be detected with a rectifier output meter. However a useful gain was obtained for signals just above noise, e. g. about 10 db improvement, where the input signal/noise ratio was initially of the order of 10–20 db. This audio selectivity was also made use of in the frequency-shift keying scheme referred to in Section 3. 1. 3.

Measurements of input signal/noise ratio have been mentioned already. In the earliest stages of the experimental work it was recognized that adequate receiver measurements would be essential to progress. It was decided, however, that the development of a good signal generator would at that time have required an unjustifiably large fraction of the available effort, since cruder and more laborious, but probably adequate, alternative methods of making receiver measurements had been devised. In general a transmitter located at a considerable distance and without unusually good screening was used as the signal source; and measured lengths of cable, or variable lengths of (sufficiently nearly) free space, or more often both, were used as attenuators. A good deal of ingenuity was required and most of the measurements were rather rough, but they were made accurate enough for the job in hand. The basic techniques were those described in Section 3.3 below.

The results of the calibration of the first laboratory model receiver are tabulated below; the transmitter at that time (summer 1937) was using sinusoidal modulation of 50 % depth on 500 Mc/s:

Carrier field strength (mV/m)	0	0.1	0.2	0.3	0.5	0.7	1.0
Receiver output (V.)	0.7 (noise)	1.1	3.0	4.85	7.8	9.9	12.1
Field strength . . .	2	3	6	10	30	100	
Output	15.8	17.7	19.9	21	23.2	26.3	

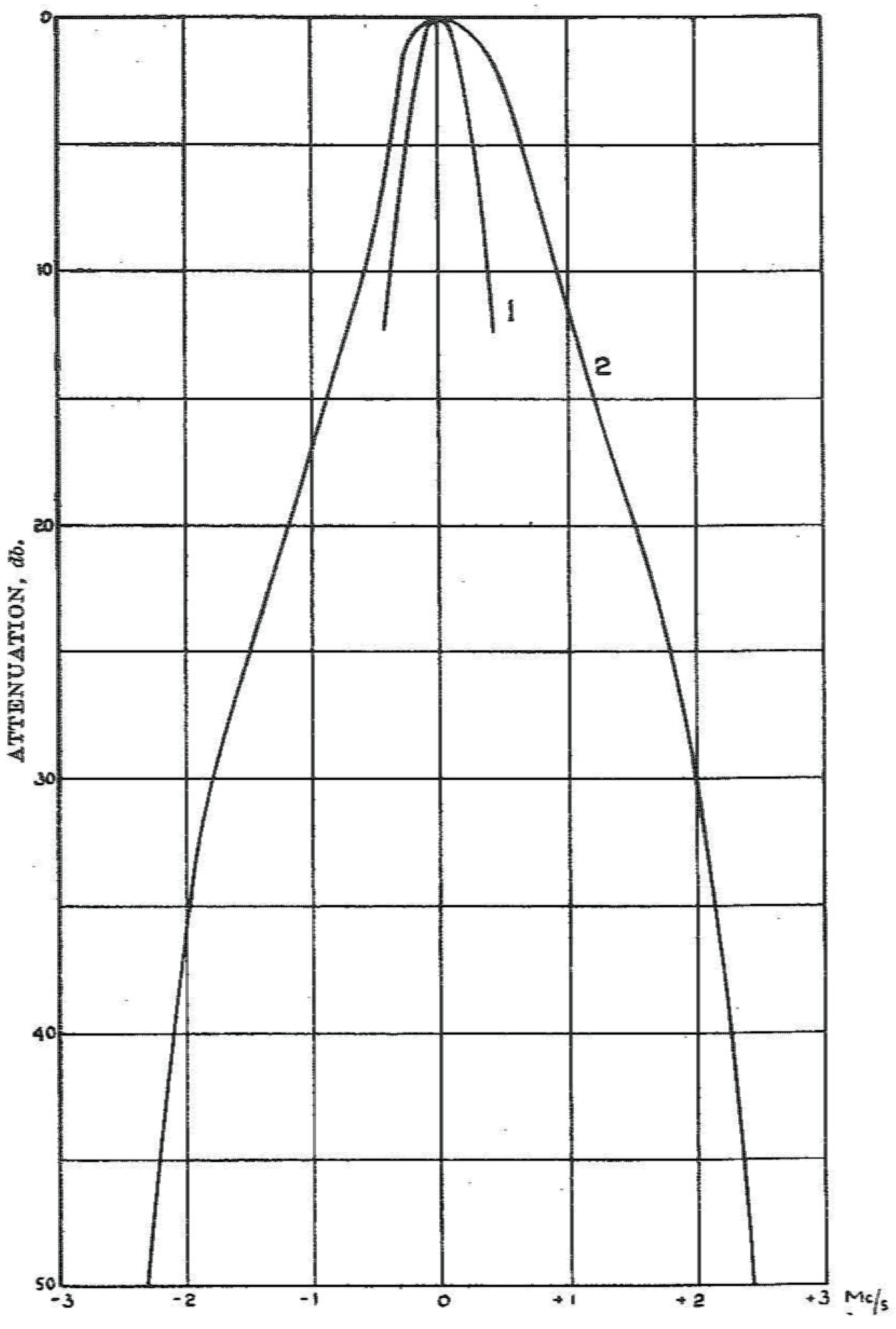
This was a composite plot obtained from several separate sets of measurements which were reasonably consistent. It is of some interest to note that a rough map of 500 Mc/s field strength contours, over a few miles round the transmitter at Wembley, was plotted at this period. Fig. 17 shows a calibration of one of the later production receivers, made after signal generators had become available. The performance recorded for the receiver referred to above is about 8 db down compared with the final models; this can probably be ascribed to measurement errors, and to actually worse performance, in about equal parts.

It is interesting to note the magnitude of the gain of the super-regenerative detector itself: an r. m. s. 1000 c/s voltage of the order of a few millivolts across 5000 ohms in the detector anode circuit is produced by a square-wave modulated 600 Mc/s signal of r. m. s. amplitude 10 microvolts applied to the 70 ohm receiver input.

Some typical receiver selectivity curves are shown in Fig. 6. Curve 1, obtained from the laboratory model with about 30 μV input at 500 Mc/s, is typical of small-signal performance; curve 2, obtained during the later trials period, is for a very strong signal of about 5 mV and was obtained at 595 Mc/s. The half-power bandwidths are about 0.4 and 0.85 Mc/s respectively. At frequencies over about 600 Mc/s the selectivity deteriorates, becoming roughly twice as broad at 700 Mc/s.

3. 3. MEASUREMENTS.

During the whole of the experimental work it was necessary to develop measurement technique to fulfil the needs – highly exacting by the standards of those days – of the operational requi-



FREQUENCY CHANGE.

Fig. 6. – Receiver selectivity curves.
curve 1 : 30 μV input.
curve 2 : 5 mV input.

rements. Some of this development has already been described in another paper, (1) but it is appropriate to mention here one or two of the more importance techniques.

3. 3. 1. *Frequency.*

One of the earliest problems was that of measurement of frequency. Early work was carried out with carefully constructed resonant line wavemeters of various types, but it soon became obvious that better methods were needed. Information on the frequency stability of magnetrons was obtained using the frequency meter referred to at the beginning of Section 3.2 and later, for most of the early work, by heterodyne measurement initially using harmonics of the local oscillator of a short wave communications receiver. Success with this encouraged the extension of this technique, and a special frequency meter was designed in 1937 for the range 500–700 Mc/s, capable of measurement of small frequency changes of the order of 1 part in 10^4 and with an absolute accuracy of a few parts in 10^4.

The method of measurement consisted in the adjustment of the frequency of the 20th harmonic of a variable oscillator to heterodyne with the unknown frequency, the resulting frequency spectrum being audible in telephones. The variable oscillator was continuously calibrated by the harmonics of a crystal of fundamental frequency 500 kc/s. Fine adjustment of the oscillator frequency was obtained by a band spread control covering at least the frequency range between two adjacent crystal calibration points (i. e. ½ Mc/s at its fundamental frequency, or 10 Mc/s at its 20th harmonic). Accurate interpolation was thus possible between two calibrating points. A separate high-Q tuned circuit, giving the unknown frequency approximately, allowed the correct harmonic of the heterodyning oscillator to be chosen.

3. 3. 2. *Power.*

Measurements of transmitter valve power were made chiefly with the aid of carbon filament lamps matched by parallel wire

---

(1) CLAYTON, HOULDIN, LAMONT, and WILLSHAW, "Journ. I. E. E.", vol. 93, Part III, p. 97 (1946).

circuits, and with care good accuracy was obtained. For use with a coaxial cable feeding on aerial load, a special coaxial lamp was devised. In this 6 carbon filaments were arranged axially around the periphery of a cylinder, and were surrounded by a tubular outer conductor. This lamp was placed in series with the coaxial cable feeding the aerial and gave the value of the current flowing to the aerial. The error in the derived measurement of power was not more than 10 %, and this due mainly to the impedance errors introduced.

Use was also made of a peak voltmeter to indicate relative output power. A special diode with small anode-cathode clearance and capacitance was arranged with its anode lead touching the inner conductor of a concentric line. The cathode, having a high resistance and suitable capacitance to earth, was connected either to an electrostatic voltmeter or to an oscillograph and gave a measurement of peak voltage. This was found very useful as a power monitor.

3. 3. 3. *Impedance.*

Early work on the measurement of impedance was carried out by means of a coaxial measuring line, with an outer conductor of 4.6 cm bore and inner conductor diameters ranging from 0.64 to 2.5 cm. A sliding vacuo-junction in a metal screening box with a coupling probe projecting through a slot in the outer, was used as relative voltmeter. Measurements of impedance of aerials, cables, connectors, etc., could be made quite conveniently and accurately.

This instrument was probably the first example of what is now commonly called a standing wave detector, for a coaxial system.

3. 4. AERIALS.

The radiator used in early trials was a half-wave vertical and fed at one end from a two wire line transformer. Radiation tests with the aid of a thermocouple receiver indicated that the variation of output power over a wavelength range of 1.5/1 was small, and the radiation from the transformer did not appear significant.

An aerial used in later work, and in final ship trials, was a quarter-wave radiator with quarter-wave compensating reactance and transformer. Fig. 7 shows the essential arrangement, in which

1 is the aerial, 2 an earthing plane of about a wavelength in diameter, 3 the compensating reactance, 4 the coaxial line transformer. Fig. 7 shows the variation of susceptance B_1 of the quarter-wave aerial with frequency, together with B_3 the susceptance of the line 3 which is arranged to be resonant at the same frequency. Values of B_1 and B_3 may be made approximately equal and opposite over a sufficiently wide frequency range, by making the diameter of the aerial sufficiently large; then the effective impedance terminating the transmission line is solely due to the conductance G_1 of the aerial. This conductance can be arranged to vary by less than

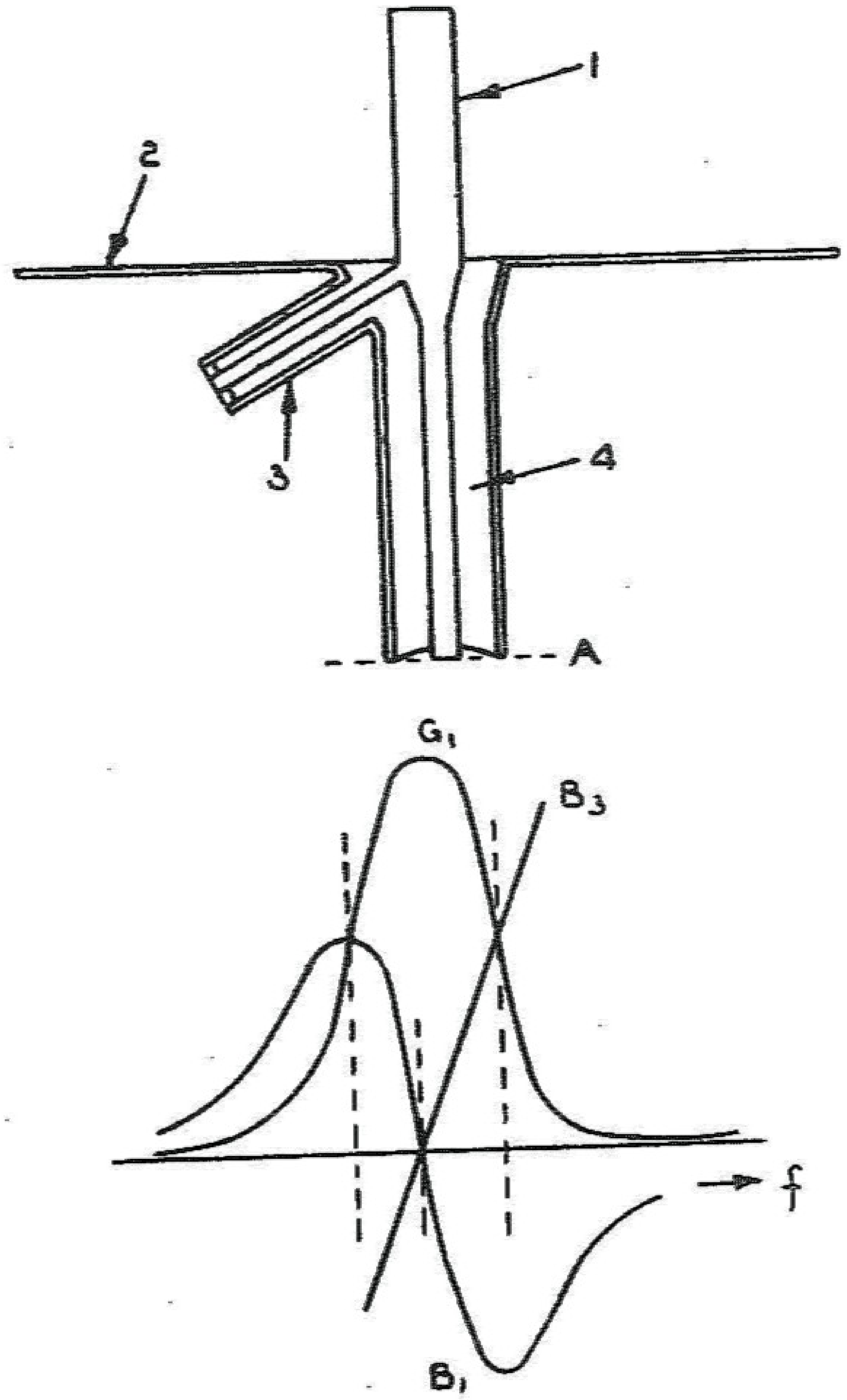


Fig. 7. – Costant–impedance aerial.

2/1 over a wide frequency range and its variation is largely compensated by the coaxial line transformer 4. With this arrangement an experimental aerial was constructed having an input impedance (measured at A) lying between 55 and 74 ohms, with phase angles lying between —18° and 0° over a 40 % frequency band. This aerial was later modified slightly for use on board ship.

3. 5. CABLES AND CONNECTORS.

When the present work started, small cables developed for television reception at 45 Mc/s had recently become available. The Telegraph Maintenance and Construction Company's type AS. 5 C coaxial was much used in the preliminary work for transmission and reception. Its average attenuation at 500 Mc/s, obtained by power and by voltage measurements, was 0.54 db/m.

For the first sea trials a lead-sheathed Pirelli-General coaxial was used; this had a flexible copper outer of 10.5 mm inside diameter, solid copper inner of 3.2 mm diameter, and air dielectric apart from blade-shaped spacers of a methacrylate resin. This cable gave a loss of 0.28 db/m at 600 Mc/s, the relatively high power factor of the small amount of solid dielectric accounting for roughly half the loss. The characteristic impedance was about 70 ohms. In the final cable the total loss was reduced by a factor of more than 2 by using polystyrene spacers, at 1.9 cm intervals, as shown at the right hand side of Fig. 8. This gave the following figures:

Frequency, Mc/s	496	593	647
Attenuation, db/m	0.10_1	0.12_1	0.12_7

The characteristic impedance remained about 70 ohms.

A standard plug and socket joint, shown in Fig. 8, was developed in collaboration with Pirelli–General Cable Works, from a similar design used in the Laboratories at lower frequencies. The large insulators which seal the cable ends were originally of low-loss steatite; substitution of polystyrene enabled a much smaller reflection at the joint to be obtained.

To provide for striking masts, relative movement of masts and bulkheads, and for quick disconnection of the transmitter or receiver, it was arranged that the cable should be fitted in relatively short lengths, dictated by local requirements; and that

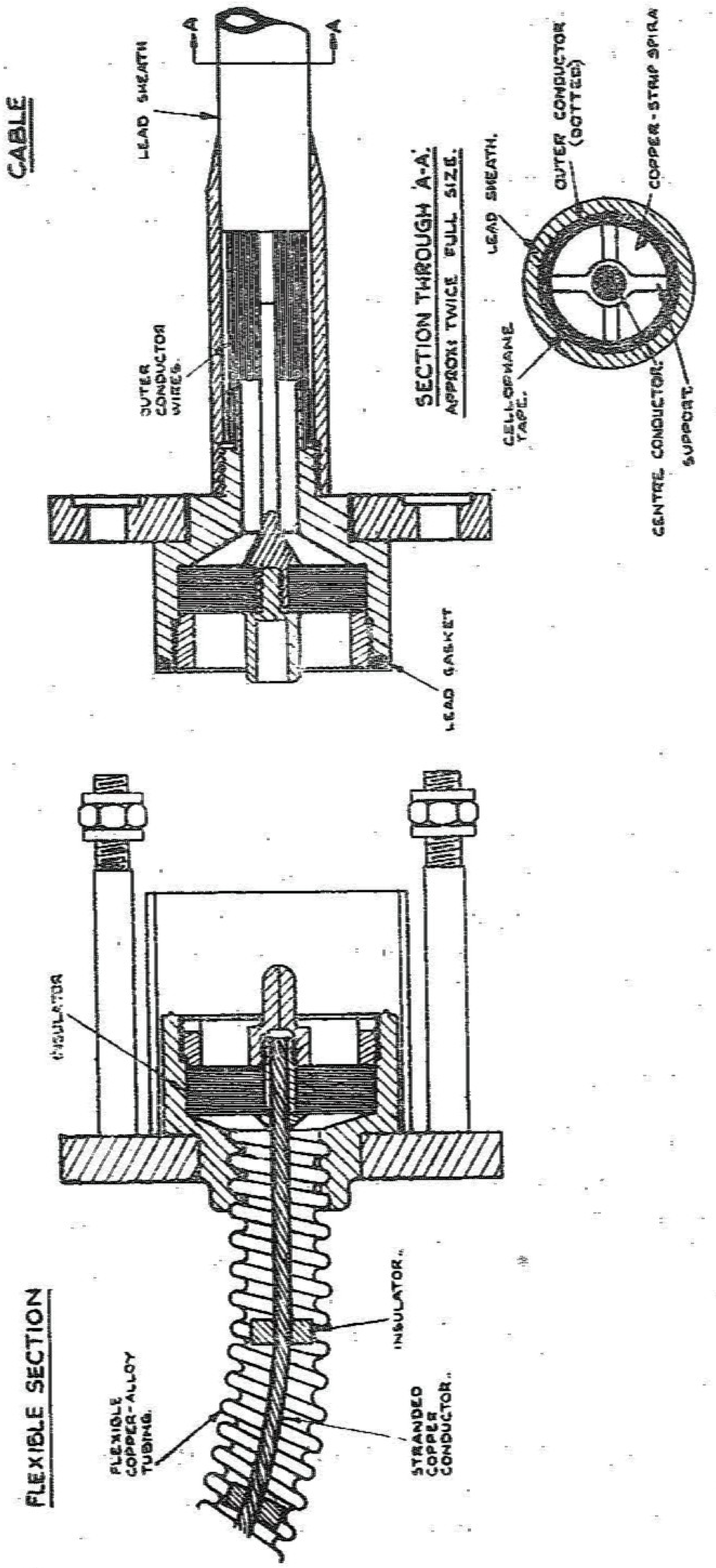


Fig. 8. – Details of plug and socket joint, cable, and flexible section.

the connections between these, and to the equipment should be made by standard flexible sections (Fig. 8, left hand side), about 1 m. long. Ceramic insulators were used at first in the flexible sections, and were later replaced by polystyrene. For the instrument connections a screwed clamping ring replaced the arrangement of Fig. 8 for clamping plug and socket together. The impedance measurements referred to in Section 3.3 played an essential part in the development of these cables and fittings.

3. 6. PROPAGATION STUDIES AND MEASUREMENTS.

Great importance was attached from the earliest stages of this work to obtaining practical experience of communication performance, and to learning how to predict performance under conditions relevant to those which would obtain at sea.

The first practical demonstrations, over land, between the Laboratories and a vehicle at distances up to 3 miles away, were given in January and February 1947; by the autumn of 1947 telephony had been received at 6 miles and telegraphy, over an obstructed path, at 8 miles. Omni-directional aerials, 17 m. high at the transmitter and 4 m. high for the mobile receiver, were used with a radiated power of the order of a watt. During this period these trials steadily became more quantitative; listening tests were soon supplemented by field strength measurements (cf. Section 3. 2).

The first estimates of the equipment performance required (to which ample safety factors were added) were made on the assumption of free-space propagation for distances of a mile or two over sea, and on the assumption that the relationship obtained for the resultant of a direct wave and an indirect wave perfectly reflected from a plane earth held at larger distances, up to near the optical limit. The results obtained by Eckersley from diffraction theory (2) were later used to give more precision to these estimates.

As a summary of recent work on propagation measurements (3) covers the general aspects relevant to the frequency band of this equipment, and as some of the results obtained in the course of

---

(2) T. L. ECKERSLEY, " Journ. I. E. E. ", vol. 80, p. 286 (1937).

(3) MEGAW, " Journ. I. E. E.", vol. 93, Part. IIIA, p. 79. *Experimental Studies of the Propagation of Very Short Radio Waves* (1946).

its development have been briefly described in another paper,⁽⁴⁾ it is unnecessary to repeat these accounts here. The results of measurements of losses produced by ships, masts and superstructure at 600 Mc/s provided the valuable general conclusion that these

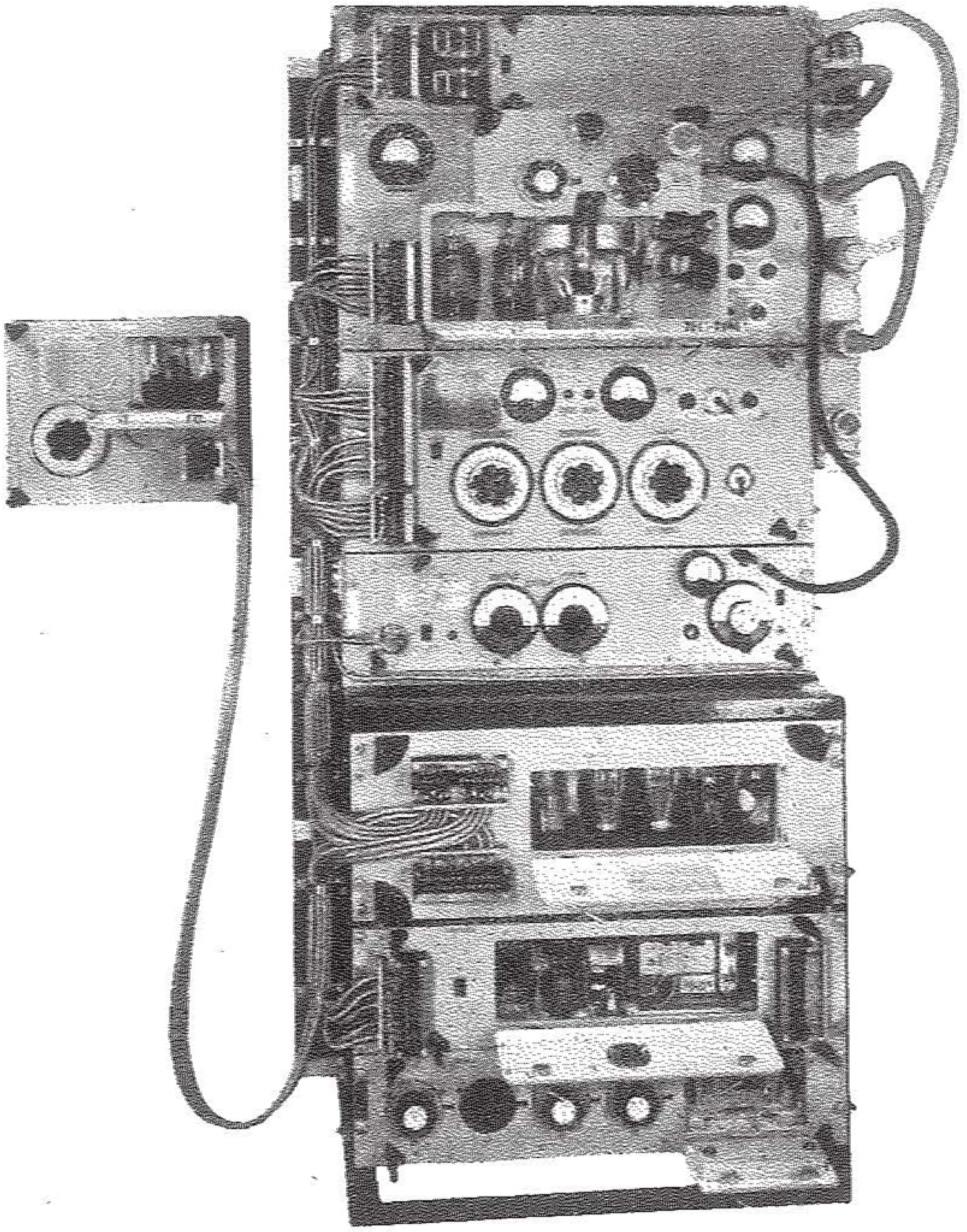


Fig. 9. – Complete transmitter, with output attenuator, keying load absorber and frequency meter.

---

(4) Megaw, "U. R. S. I. General Assembly", Paris, *Some Effects of Obstacles on the Propagation of Very Short Radio Waves*; see Sections 3. 1 and 6. 1. (To be published shortly in "Journ. I. E. E.") (1946).

could be estimated with useful accuracy by means of simple Fresnel diffraction calculations for the cases which were of practical importance. It was concluded that, even in the case of an aircraft carrier mast 0.46 m. in diameter, an aerial mounted at a practicable distance from the mast (about 3 m. in this case) would suffer a diffraction loss of only about 5 db in the shadow of the mast. This result was of great importance in making plans for the subsequent fitting of the equipment.

4. – General description of final equipment.

The experimental work outlined in Section 3 led to the building of a laboratory model for one-way trials at sea in May 1938. Following these a prototype equipment was constructed in the Laboratories, and was satisfactorily tested in 2-way operation in April 1939. The G. E. C. Radio Works undertook the production of 12 of these sets with the object of full trials at sea in the spring of 1940. Two further sets having facilities for remote control of frequency were finally supplied in addition.

Fig. 9 shows a photograph of the complete Transmitter outfit, with all doors open and protective covers removed; Fig. 10 shows the receiver.

4. 1. TRANSMITTER OUTFIT.

The Transmitter outfit was divided up into a number of units mounted on 28″ panels, and these may be identified in Fig. 9 with the aid of the key. Apart from a d. c. supply for keying, it was fed entirely from 230 V. 50 c/s supply.

4. 1. 1. *Transmitter.*

The transmitter (unit 2 in Fig. 9) carried the magnetron and its r. f. circuits; Fig. 12 illustrates the construction of the r. f. circuits and tuning mechanism. In Fig. 9 the magnetron can be seen mounted in a plug-in holder between the poles of the permanent magnet. The magnetrons were adjusted for position and locked in their holders before delivery, and could therefore be replaced like any normal valve. Two flexible leads from the magnetron anode segments plugged into the horizontal balanced line circuit visible in Fig. 12; this was tuned by a moving bridge, driven by the right hand knob visible in this Figure. A flexible coaxial cable led power from a coupling tap carried by this bridge, through a tube carrying the monitoring diode mounted in a tee-piece, to the output socket visible on the front of the panel. A relay-operated switch was provided to open-circuit the inner conductor when the key was up, and so minimize the effect of any residual radiation on a local receiver. The position of the coupling point relative to the movable bridge could be varied by turning the central knob. In order to balance the effect of the unbalanced cable load, a half-wave coaxial line, visible in the figure, connected the cable tapping point on one conductor of the oscillator line to the corresponding point on the other conductor. All the oscillatory circuits in this equipment were silver plated and rhodium flashed; this technique has since been widely used.

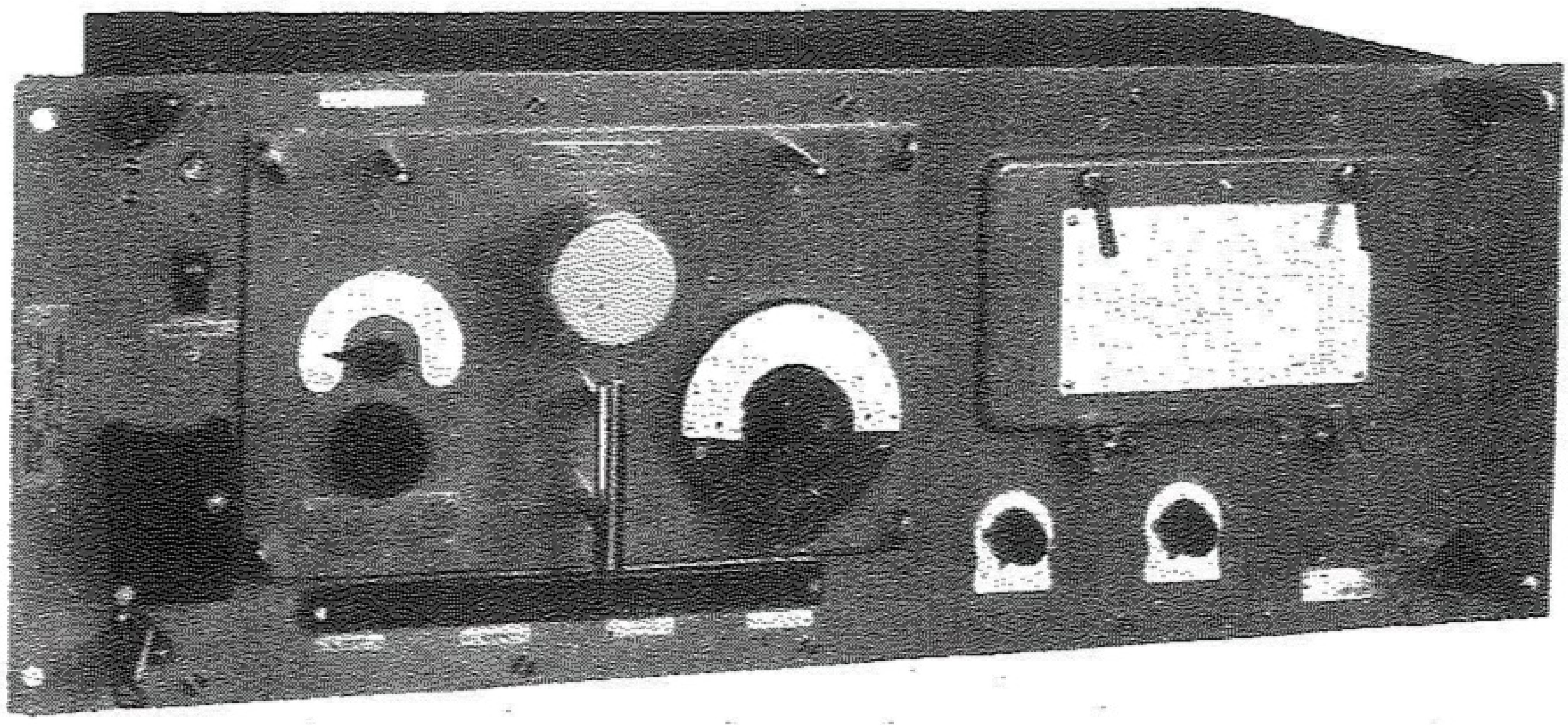


Fig. 10. – Receiver.

In the standard transmitter outfit four different stabilized frequencies (515, 530, 635 and 650 Mc/s) could be obtained, four plug-in resonators being supplied; those not in use were mounted in a "Stowage Unit" at the bottom of the transmitter rack. This unit also carried a spare magnetron. The resonator in use is visible, not quite fully inserted in its mounting, in Fig. 12; the spring-loaded coupling connection from it to the oscillator circuit can be clearly seen. The resonator was held in position by a bayonet cap fitting. On the right of the oscillator circuit, near the front, can be seen

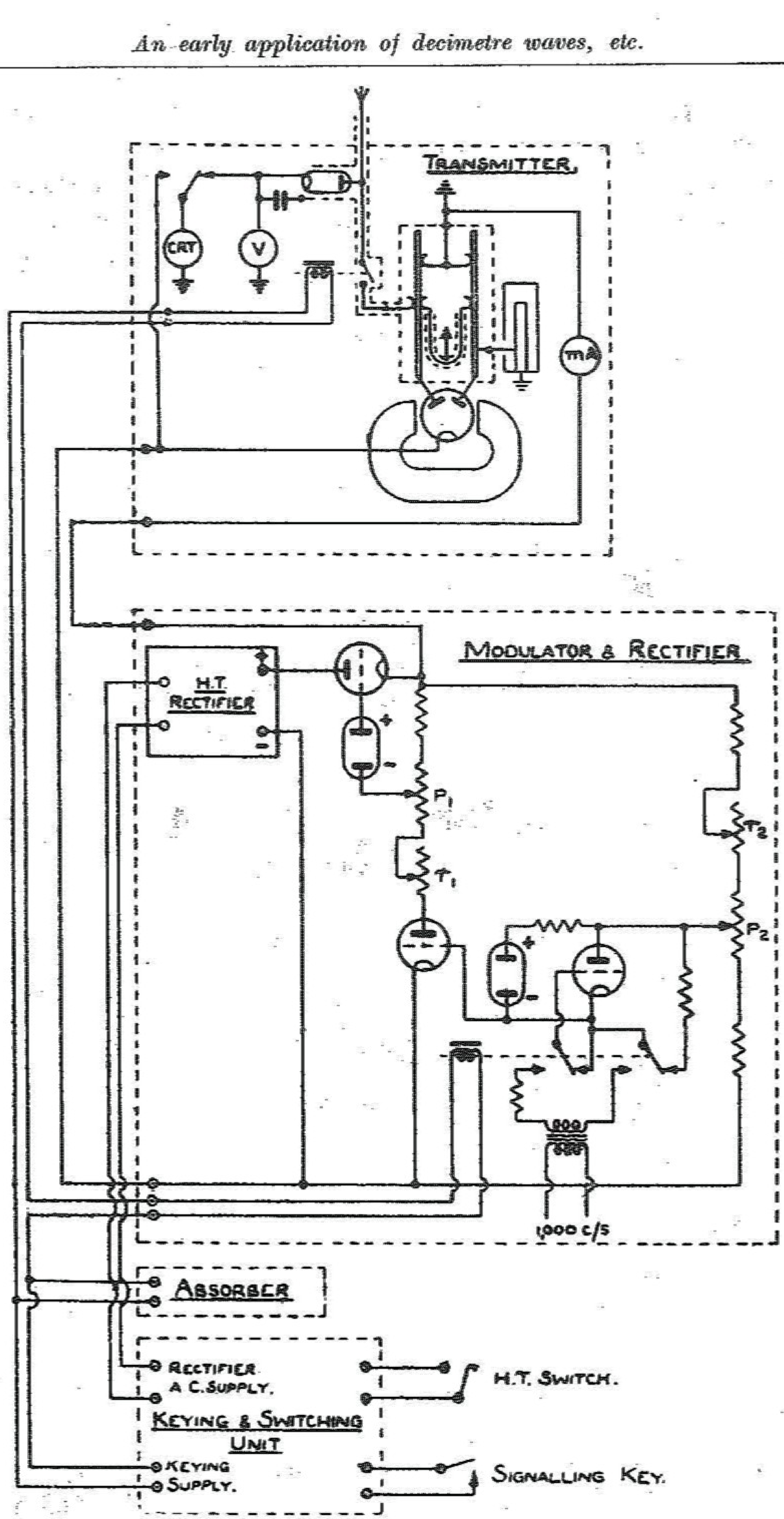


Fig. 11. – Simplified circuit of transmitter outfit.

a coupling probe, damping resistance, and flexible connector for the transmission of a signal to the frequency meter.

This panel also carried a meter indicating the output peak voltage, and a small cathode ray tube for monitoring the output r. f. envelope or the anode voltage waveform, as well as magnetron filament voltage (a. c.) and anode current meters, and two spare high voltage rectifier valves which were kept pre-heated (see Fig. 9).

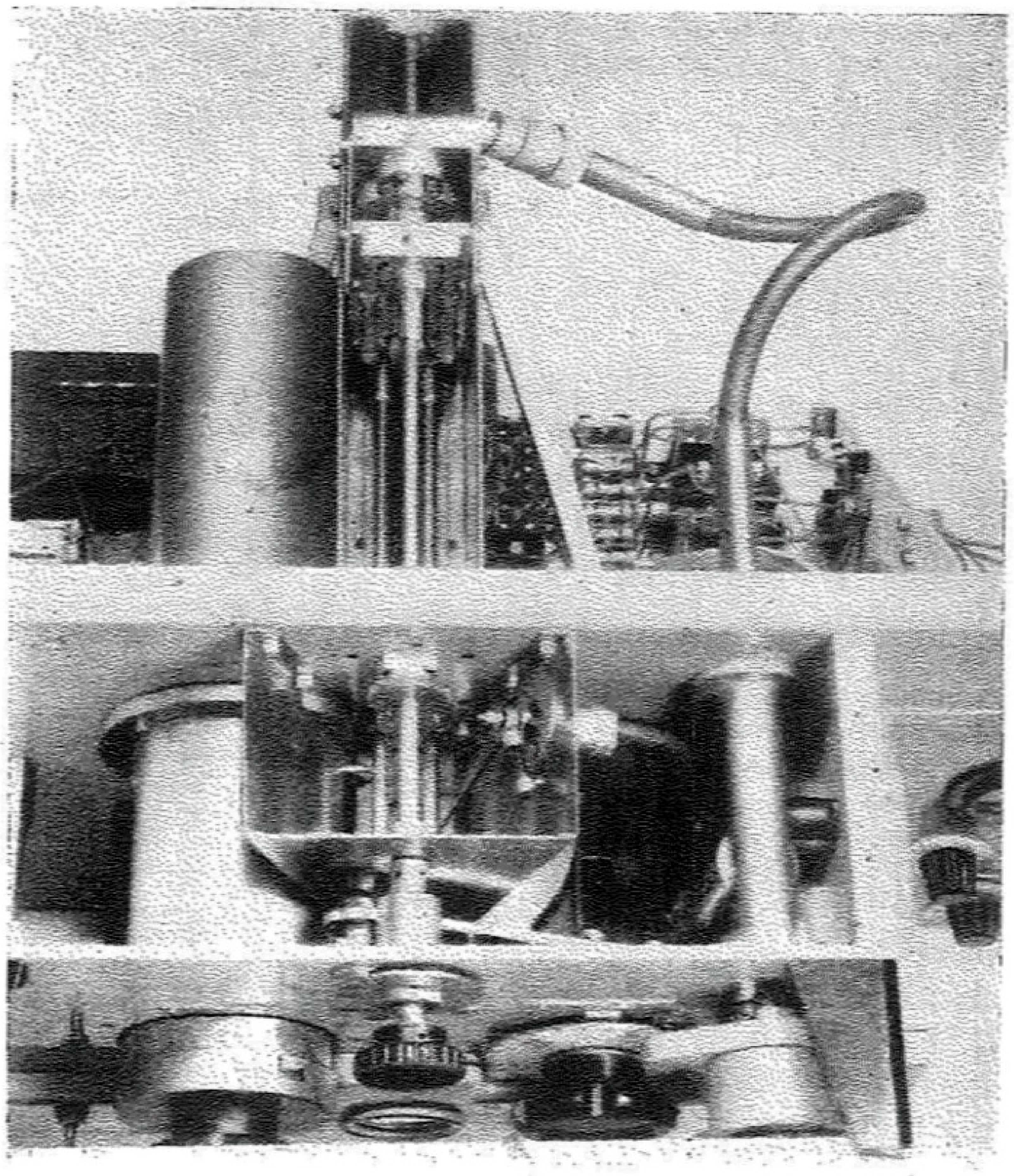


Fig. 12. – Interior view of transmitter oscillator panel.

Fig. 11 shows a simplified circuits diagram of the units of the transmitter outfit.

4. 1. 2. *Modulator and rectifier.*

The modulator and rectifier (units 3 and 5 respectively) together contained all equipment for the stabilized and modulated power supply for the magnetron, the modulator carrying all controls and meters and the rectifier all valves.

Of the three large controls carried by the modulator, the left hand one in Fig. 9 controlled magnetron filament voltage, the middle one H. T. rectifier output voltage, and the right hand one stabilized value of the anode voltage (it operated resistances r_1 and r_2 in Fig. 11, ganged together). Two small knobs (top right) controlled the present potentiometers P_1 and P_2 of fig. 11, by means of which the stabilizer was first lined up, with the aid of the two meters and a selector switch (see Section 3. 1 4).

4. 1. 3. *Absorber.*

In order to maintain the power consumption from the ship's mains approximately constant during keying, and so minimize any effect of keying surges on other equipment, an absorber (unit 8) was used. In this, power of magnitude adjusted to correspond to the input to the magnetron with the key depressed was dissipated in a resistance in the absorber when the key was released. The switching of the absorbed load was effected by means of gas-filled triodes.

4. 1. 4. *Keying and switching unit.*

The keying and switching unit (7) contained rectifier and relay equipment, by means of which keying and switching of the transmitter could be effected, either remotely or locally. It also provided for certain switching operations required in routine testing and tuning, and for interlocks required for the protection of personnel and the prevention of incorrect operation. All panels having doors giving access to high voltage were fitted with interlock switches, so that opening a door caused the mains supply to be out off.

4. 1. 5. *Frequency meter.*

A heterodyne frequency meter (unit 4), designed on the basis of the arrangement described in Section 3. 3. 1, was incorporated in the transmitter outfit. The front of this is visible in Fig. 9 and a rear view is given in Fig. 13.

In Figs 9 and 13, the two left-hand dials are the fine and coarse tuning controls of the heterodyning oscillator, which covered 24–

37.5 Mc/s. This oscillator can be seen, in Fig. 13, in the shielded compartment farther from the front panel. The front left-hand compartment contains the 500 kc/s calibrating crystal oscillator. For this a single pentode acts as a triode oscillator at 500 kc/s and as harmonic generator. For the latter purpose, its anode circuit is automatically tuned by a ganged circuit to that harmonic required to calibrate the variable oscillator at any given setting of its tuning dials. The right-hand dial in Fig. 9 controls the tuned input circuit, clearly visible on the right in Fig. 13 with its probe-coupled input and output cables. This circuit had a Q-factor of about 500, and a calibration accuracy of about ± 5 Mc/s. It feeds an acorn used as a diode, whose modulation-frequency output is indicated after amplification on the meter above the tuning dial. Thus an approximate frequency reading could be obtained immediately, allowing the correct heterodyne signal to be located on the main tuning dials without delay or uncertainty. All dials are calibrated in the final frequency, and not in sub-multiples, so that operation is quite straightforward.

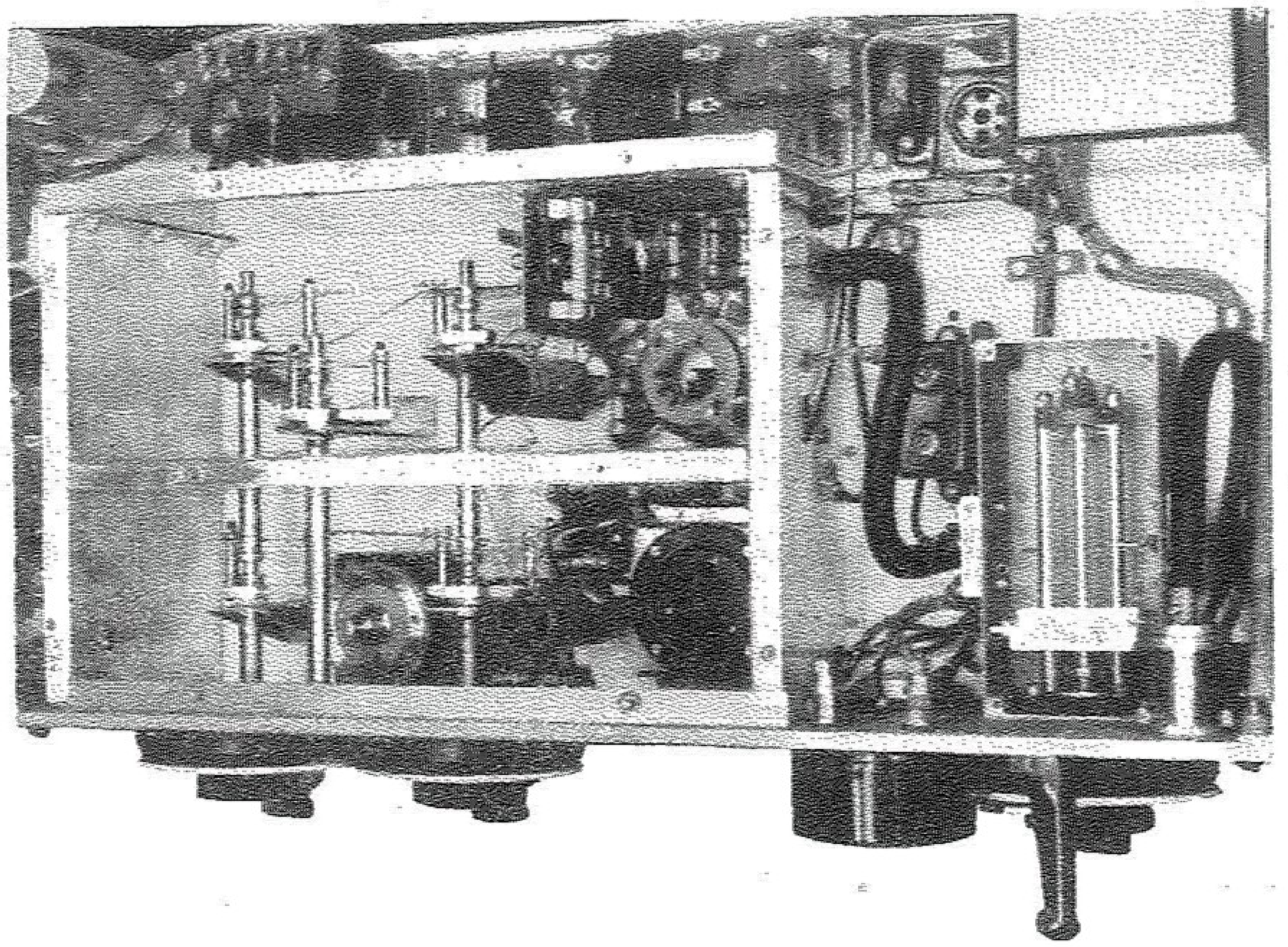


Fig. 13. – Interior view of frequency meter.

4. 1. 6. *Performance of transmitter.*

Typical operating conditions at the extremes and middle of the frequency band, with a magnetic field strength of 900 oersteds, were:

Frequency, Mc/s	500	600	700
Anode voltage	800	950	1100
Anode current (pulse), mA.	150	130	110
Output (pulse), W.	30	25	15

With the square-wave modulation the pulse figures are double the mean.

The 3/4 wavelength oscillatory circuit, which had considerably simplified circuit design for this frequency range, was quite satisfactory with normal loading.

The voltage-stabilizing, modulating, and keying arrangements worked very well.

The results on frequency stability, one of the main goals of the development, were very satisfying. A change of mains voltage by the required ± 5 % normally produced no detectable frequency change, i. e. not more than about 1 in 10^5. Varying the oscillatory circuit length over a range, which would have given over 50 Mc/s change without the resonator, gave only about 1 Mc/s with it. This small residual rate of change was used when obtaining standard settings to bring the frequency exactly to the nominal value for each resonator. Changing a magnetron, without altering anything but the coupling adjustment, gave changes of up to a few tenths of megacycle. In a text to determine the effect of varying the length of coaxial line between output socket and aerial, using a telescopic section, the maximum frequency pulling for a typical installation was 0.07 Mc/s at 507 Mc/s and 0.05 Mc/s at 660 Mc/s. The actual standing–wave ratio was not determined.

A continuous run of several days, on typical mains, showed no frequency change in excess of 1 in 10^4.

4. 2. RECEIVER.

The electrical arrangements of the final receiver were sufficiently similar to those described in Section 3.2, and illustrated in the circuit diagram Fig. 5, to need no detailed description here. In Fig. 10

the removable r. f. unit can be seen on the left, carrying on the panel the "aerial" (preselector) tuning control, the input socket, and the oscillator tuning dial. The reaction and gain controls, and the two output jacks, are below the door which gives access to all the valves, except the detector acorn.

The inside of the r. f. unit is shown in Fig. 14, with the acorn removed to show the tuning condenser. The preset bridge with its scales (reading 4.4 cm) can be seen near the upper end of the oscillator circuit conductors. The half-wave preselector line, tuned by the rack and pinion on the right, was folded for compactness. Its tuning scale was directly calibrated, with an accuracy of ± 5 Mc/s.

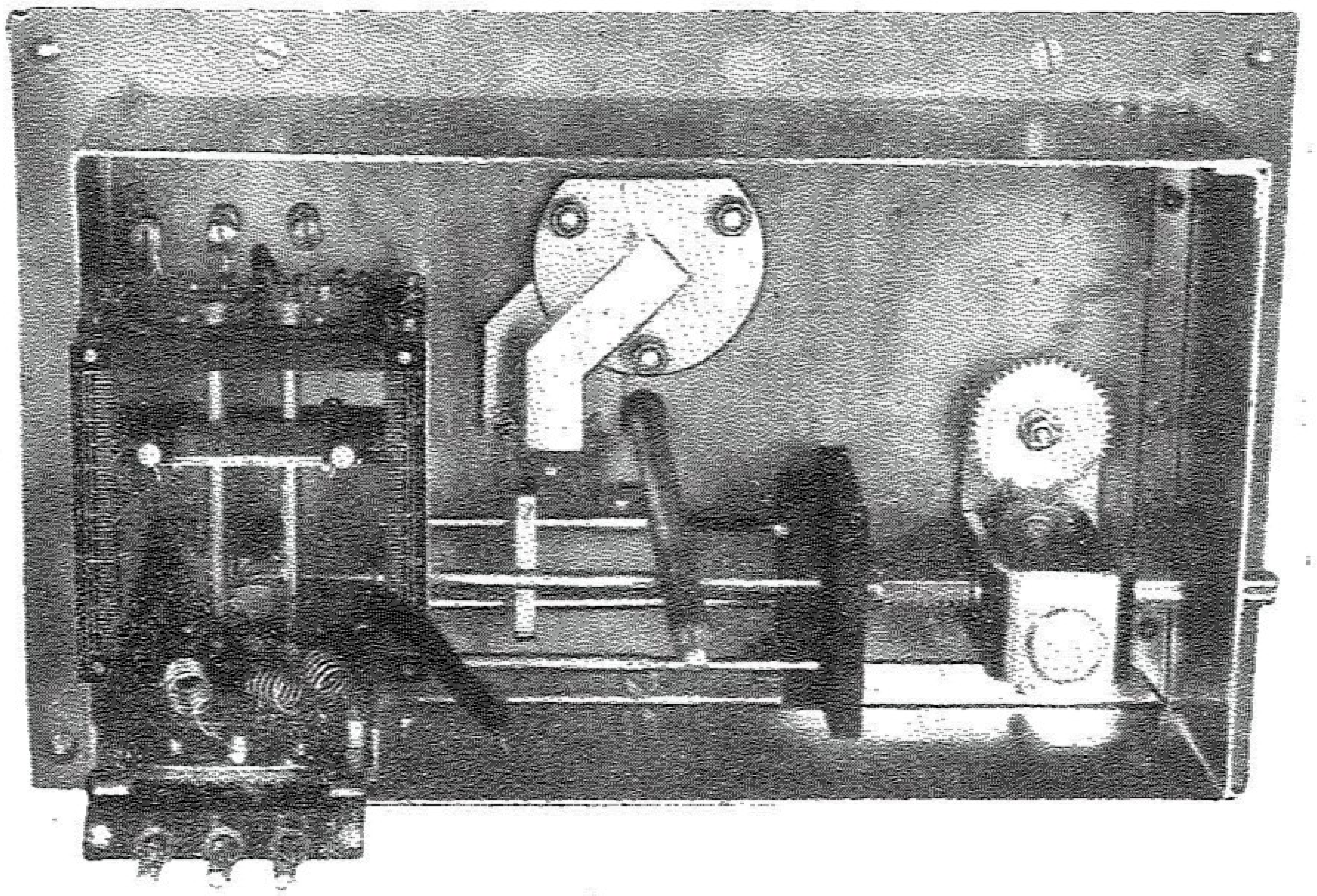


Fig. 14. – Interior view of receiver H. F. unit.

Four successive settings of the oscillator bridge were required to cover 500 to 650 Mc/s, and two more to reach 700 Mc/s, allowing reasonable overlap between ranges. The tuning scale was reasonably linear in frequency, except near the high frequency end, with an average slope of about 0.5 Mc/s per angular degree. Typical detector anode currents ranged from 2 to 8 mA.

The resetting accuracy, after changing tuning range, was about 1 Mc/s; with different receivers at the same tuning settings the spread in frequency was 5 to 10 Mc/s, using the same acorn; and the normal spread for changing acorns was 10 to 15 Mc/s. Maximum frequency pulling by the preselector was from 2 to 5 Mc/s, depending on the frequency.

Individual frequency calibrations were not provided, the receiver normally being tuned to the local transmitter frequency. The transmitter frequency meter could be used if necessary.

Selectivity (see Fig. 6) was such that a transmitter 100 metres away did not interfere with a weak wanted signal, if its frequency differed by more than about 3 Mc/s in 500 Mc/s or 6 Mc/s in 700 Mc/s.

Frequency variations with ± 5% change in mains voltage were larger than for the transmitter, but were insignificant in practice.

A comparison of five production receivers on the same transmission showed a spread in sensitivity corresponding to only 0.5 db change in signal input. An input signal of about 1.5 μV was just audible; assuming the effective bandwidth was that of the r. f. part of the receiver, and that a signal equal to noise was one which gave an output voltage double that given by noise alone, the noise factor was about 20 db (cf. Fig. 17).

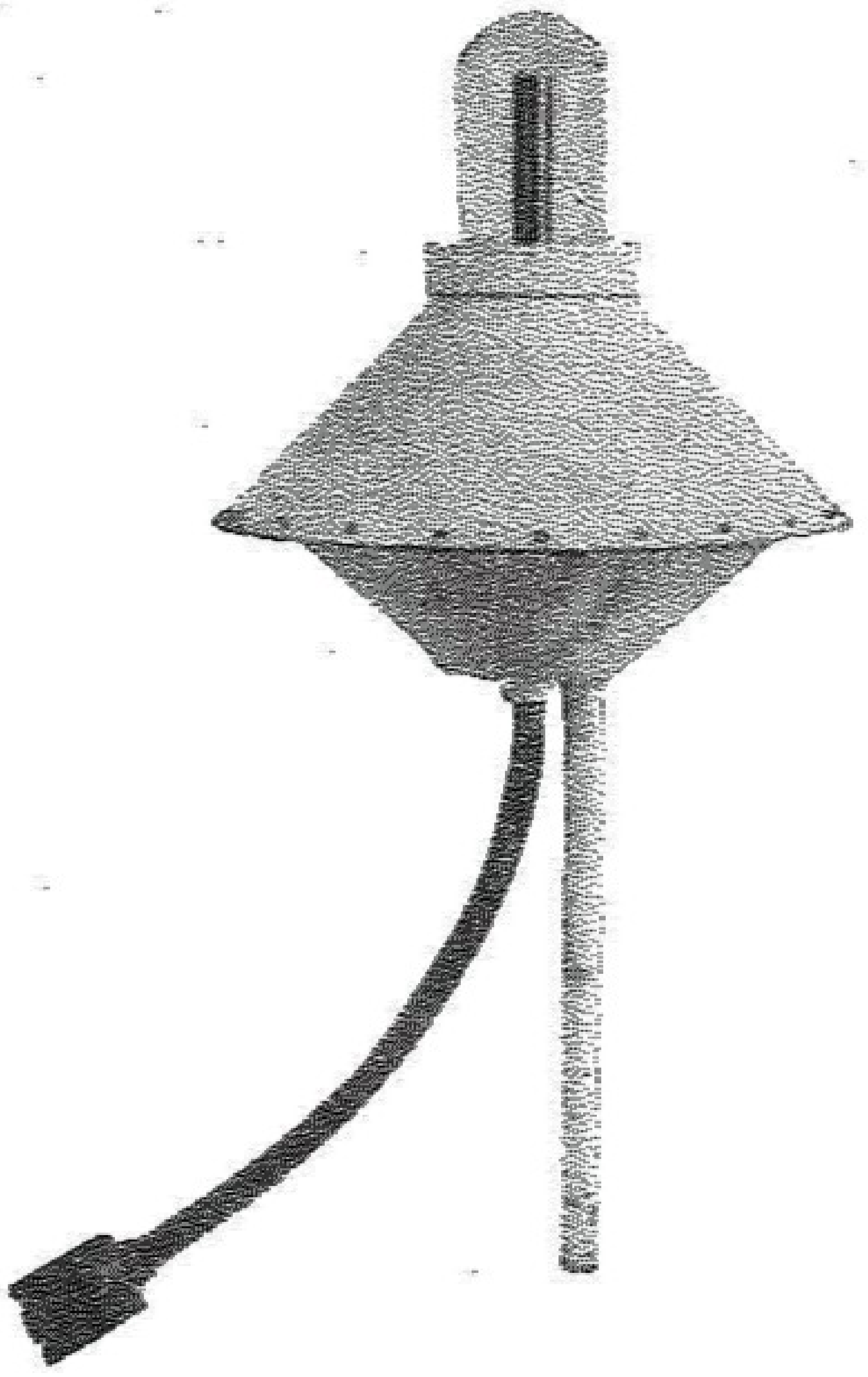


Fig. 15. – Aerial.

4. 3. AERIALS AND CABLES.

Fig. 15 shows the type of aerial fitted; the aerial proper is under a protective glass dome. The "earth plane" of Fig. 7 has here become a cone; this was to give a better vertical plane radiation diagram. From this diagram a gain of about 1 db over a half-wave dipole was indicated; a direct comparison gave about the same received signal. It was also concluded that with the final aerial a roll of ± 20 degrees would give only 1 db change in signal; this was a considerable improvement over the experimental aerial.

Painting the glass dome had no measurable effect; covering it with about 5 cm thickness of snow gave about 6 db loss.

The cable system fitted was as indicated in Fig. 8, with the addition of steel wire armouring over the lead sheath. The total loss varied from about 3 to 10 db according to the size of ship and position of the equipment. A typical aerial installation in a destroyer is shown in Fig. 19.

The Attenuator (unit 9 of Fig. 9) contained two lengths of relatively high-loss cable, by means of which an extra attenuation of 6, 12, or 18 db could be introduced between transmitter and aerial for short-range working.

4. 4. REMOTE FREQUENCY-SWITCHING.

For certain possible applications of the equipment, it was desirable to be able to make a rapid change between at least two alternative communication channels. As noted above, two additional sets were produced with this facility provided in the transmitters, two alternative frequencies being available from each of 8 different resonators; the 16 possible frequencies lay between 500 and 680 Mc/s, and the switchable steps ranged from 8 to 12 Mc/s. Frequency switching was not provided in the receivers.

The resonator frequency was changed by applying an impulse to a latch-in relay, which carried out the following operations: applied 75 V d. c. to the appropriate switching coil of the special resonator; illuminated the appropriate local and remote indicator lamps; and altered the stabilized anode voltage by the appropriate small amount. It was found unnecessary to make any other change in transmitter settings.

The resonator construction is shown in Fig. 16. Frequency switching was effected by altering the length of the inner conductor, which had a bellows near the free end. An armature carried by the operating shaft was attracted by the field of one or other of the operating coils against the accurately machined face of its mild steel pot. The left-hand pot was adjustable by rotation on a screw thread, in small discrete steps each corresponding to about 0.05 Mc/s, to set the movement of the armature to correspond to any desired frequency change up to about 15 Mc/s. An adjusting screw for setting the lower frequency to the exact required value can be seen at the end of the inner conductor. Both these adjustments were made and sealed in production. Spring contacts were provided to carry the operating current, about 100 mA, to the coils when the resonator was plugged in.

Measurements on this equipment showed that the resetting accuracy on frequency switching was extremely high: better than 1 part in 10^4. When operated with two receivers, each tuned to one of a pair of frequencies, with their outputs paralleled, there was no detectable discontinuity in morse signalling, when the frequency was switched.

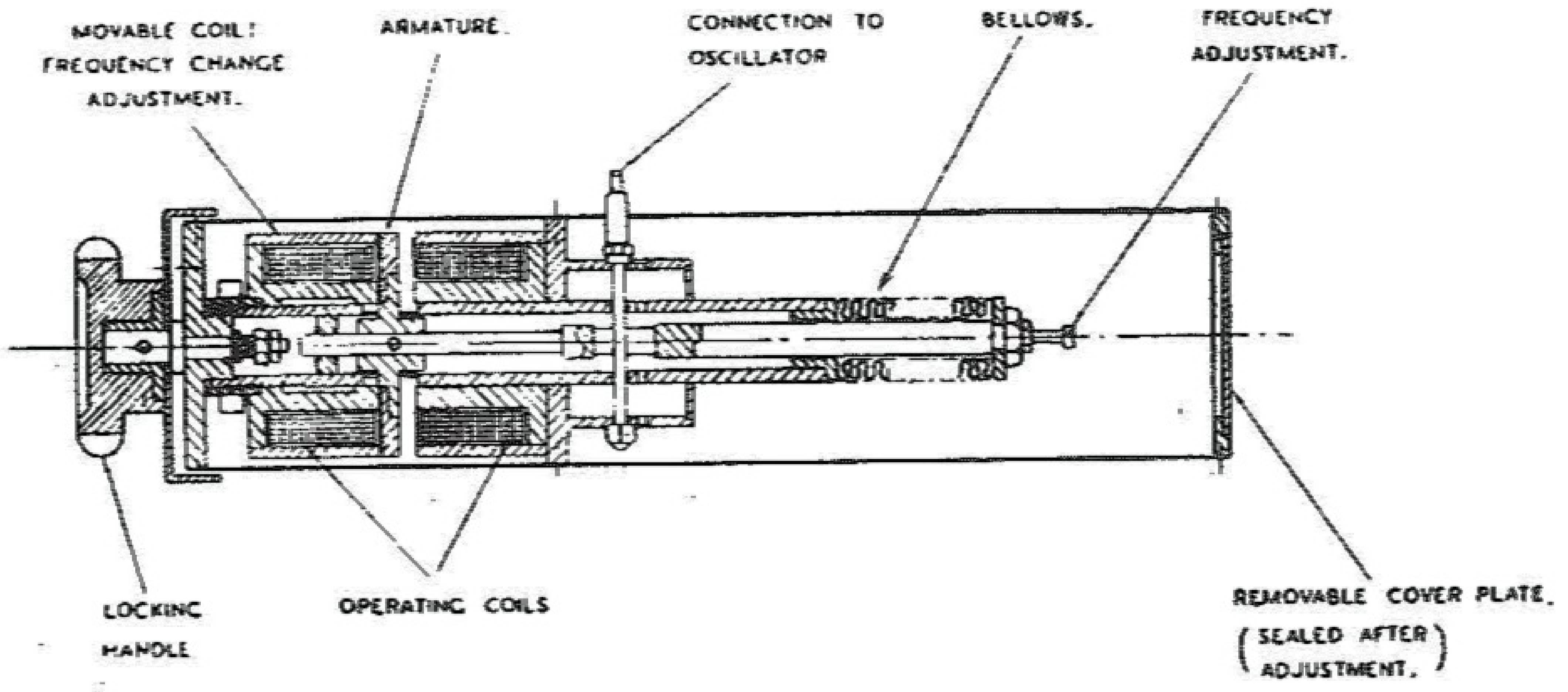


Fig. 16. – **Stabilizing resonator for remote frequency-switching.**

5. – Trials and performance.

Before discussing some of the results available from trials, it may be useful to note the range performance to be expected from the final equipment, on the basis of measurements made under laboratory conditions and of calculations assuming normal atmospheric refraction.

A typical amplitude calibration for the receiver, at maximum gain, is shown in Fig. 17. The departure of this curve from a logarithmic law above about 5 volts output is largely caused by a non-linear shunt across the low-impedance output which was included to avoid excessively loud signals from the local transmitter. (The range of input to be handled in small ships was of the order of 100 db). The input at which the curve starts, about 3.5 db above 1 μV, is that which was just distinguishable from noise to a skilled and undisturbed operator; a keyed signal some 7 to 8 db

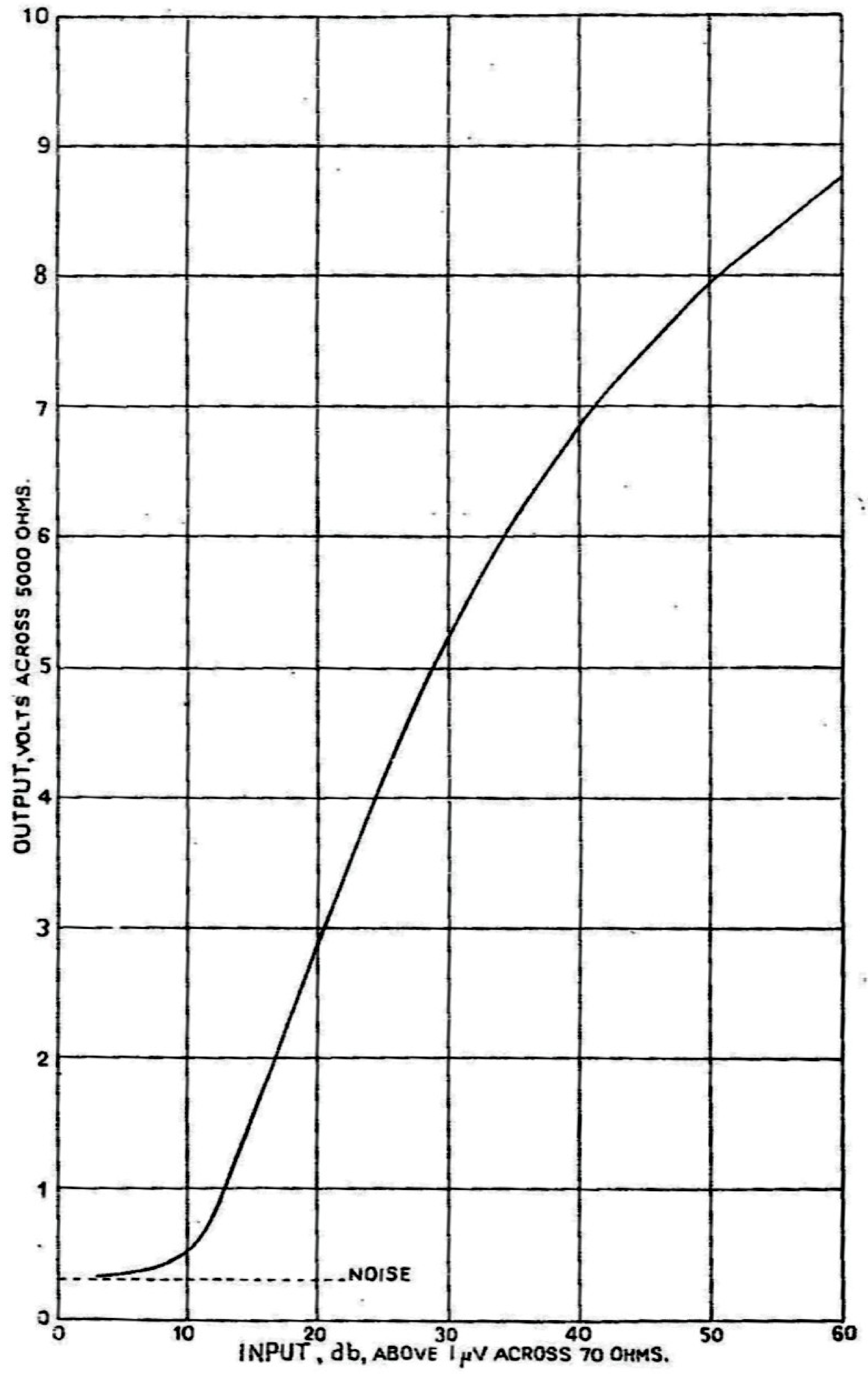


Fig. 17. – Amplitude calibration of receiver

higher, which is roughly that giving equality of signal and noise power at the input, was just continuously readable under the same conditions.

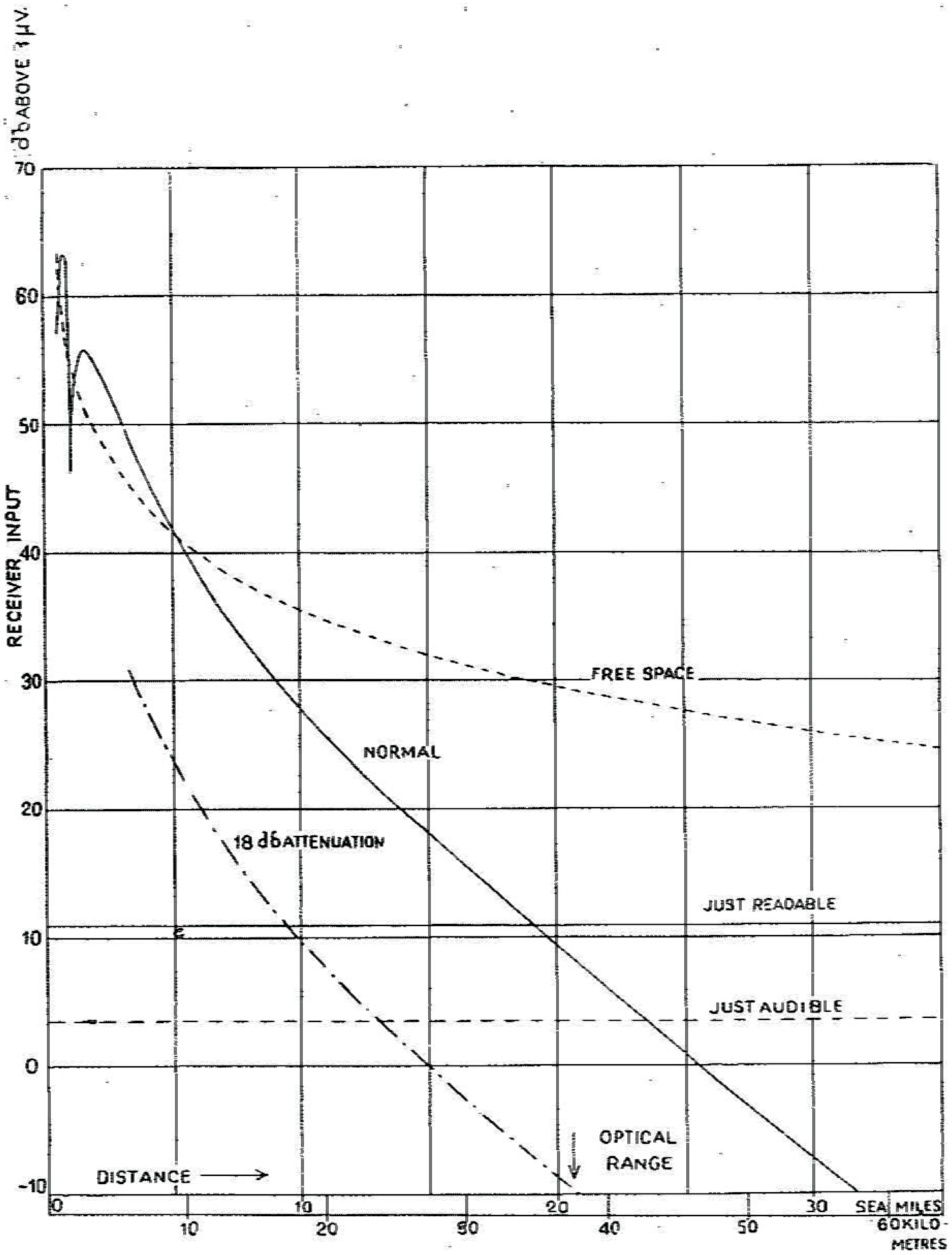


Fig. 18. – Calculated range performance for conditions typical of destroyers; aerial heights 70 feet; cable losses 4 db each end. Frequency 600 Mc/s; output 25 W (pulse).

In Fig. 18, the calculated relationship between receiver input and distance is given for a typical installation operating at 600 Mc/s; the free-space curve, and the effect of introducing the full output attenuation available at the transmitter, are shown. The "just audible" and "just readable" levels are derived from Fig. 17 as described above.

The early trials over land have already been referred to in Section 3.6. Later measurements over land, obtained during trials of the sets fitted with remote frequency-switching, are of interest in providing some data on the variation of performance with frequency. Results for 16 frequencies between 500 and 670 Mc/s indicate a total range of variation of about 10 db. The form of the results suggested that path-difference effects were probably contributing to the variations observed. Calculation for the conditions assumed in Fig. 18, including the dependence of transmitter output and cable loss on frequency, predicts a monotonic decrease in receiver input of 7 or 8 db between 500 and 700 Mc/s, for free-space transmission; for ship-to-ship transmission over distances between about 3 and 30 km (within optical range) this decrease is slightly reduced, and the curves of Fig. 18 may be expected to hold within about ±3 db for the whole frequency range.

It is obvious from Fig. 18, and had been recognized early in the project, that ranges from a ship to an aircraft well above the horizon would be much greater than to another ship. Trials were arranged in 1941 between a ground transmitter on 535 Mc/s and an aircraft carrying an omni-directional receiver. These showed that the received signal at a height of 5000 metres and a distance of 130 km was within a few db of the estimated free-space value. On another occasion signals were heard out to 190 km at the same height and could probably have been received at still greater distances.

In May 1938 the first (one-way) sea trials were carried out between two destroyers, using the laboratory model of the complete equipment. It was estimated before the trials that the maximum range for a just audible signal should be about 17 miles (31 km) which, allowing for about 8 db larger cable losses and about 3 db worse receiver sensitivity, agrees with the recent calculations of Fig. 18. In the early runs, using an end-fed vertical half-wave dipole, which was an "improved" but untried version of that used ashore, both range and radiation diagrams were far from what was expected. The aerials, at the masthead, were then replaced by a design similar to that of Fig. 7 and ranges within a few miles of the calculated value were obtained, with radiation polar diagrams which were circular to within 1 db. It was concluded that, under practical conditions, a certain communication range of 5 miles (9 km) could be relied upon; that signals would normally be lost at about 10 miles (18 km); and that surface interception beyond 20 miles (37 km) was very improbable. On a single occasion during these trials, on the afternoon of a particularly fine day, a strong signal (estimated later to have been 10–15 db above the normal calculated value for a standard atmosphere) was received at 18 miles (33 km), when the aerials were both at a height of about 45 feet (14 metres). This was the only occasion, during the development of this equipment, on which clear evidence of super-refraction was obtained; it was dismissed, perhaps too readily, as not being of much practical significance.

Early in 1939 two-way trials were carried out over land, over an obstructed path giving a received signal equal to that expected for a clear path of 9 miles (16 km) over sea. Easily readable signals, with satisfactory "listening through", were obtained.

The measurements made to determine the diffraction losses produced by masts and superstructure have already been referred to in Section 3. 6.

The twelve production equipments, mentioned earlier, were intended for full-scale trials in the fleet, under controlled conditions, in the spring of 1940. They were used, under wartime conditions, to fit one capital ship and a flottilla of destroyers. Fig. 19 is from a photograph, taken from another ship, of one of the destroyers on escort duty. The details of this venture are outside the scope of the paper, but it is of interest to note that after a year's experience the set was stated to have been "most successful in operation", and was retained in service in spite of difficulties as regards maintenance. These difficulties were, in general, not surprising in an equipment which used many techniques and components new to the service, and which was still rated as experimental, but one important lesson was learnt from them: this was that the use of un-pressurized air-dielectric cable in ships was unsatisfactory, in spite of considerable precautions in design and test.

The amount of quantitative data obtainable from trials under operational conditions is usually not large, but a number of facts of technical interest emerged.

A range trial on 635 Mc/s between two destroyers, with signal strengths recorded on the "R" scale, showed a steady decline in strength from about 1 mile to 17 ½ miles (2 to 32 km) at which "communication did not fail, but signals were only just audible". This probably corresponds to the "just readable" level in Fig. 18 and to a range performance within a few db of that calculated;

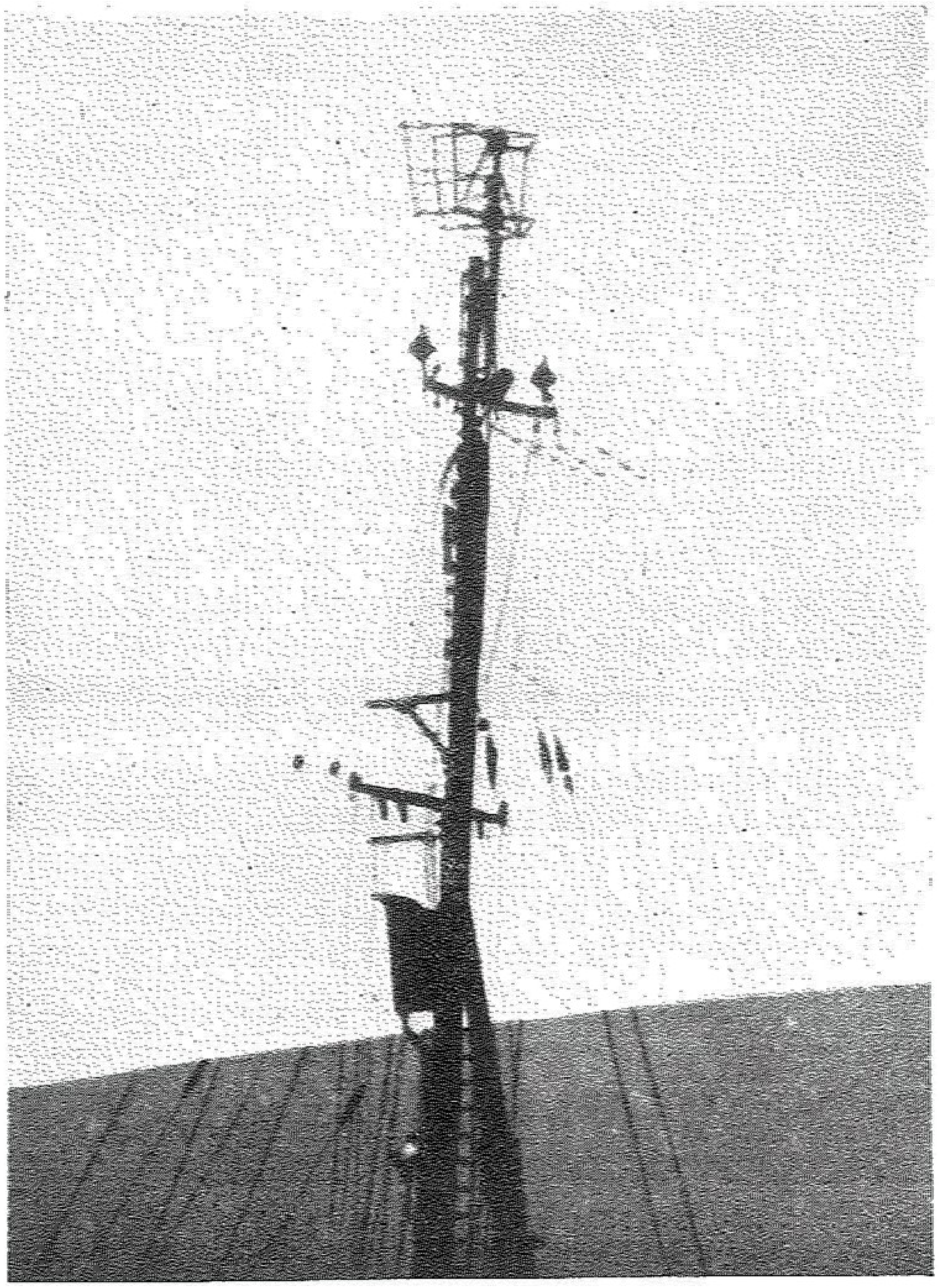


Fig. 19. – Foremast of H. M. S. Matabele, showing aerials at the ends of the upper yard arm.

meteorological records indicate that normal propagation was probable at the time. The signals received in the two ships were very similar, when the relative bearings were such that both masts intervened for one direction of transmission, while transmission in the other direction was unobstructed.

On another occasion, for which the meteorological situation is not known, two-way working was reported between two other destroyers out to about 22 miles (40 km), and signals were just readable one way at about 24 miles (44 km). Another report, without details either of equipment or weather, quoted a range of about 10 miles for satisfactory communication between destroyers.

It is clear from these results that, ideally, the specified range performance could have been achieved with much less than the normal transmitter output; in fact Fig. 18 shows that the maximum attenuation provided should have given just adequate performance and would have reduced the range to a similar receiver in an aircraft to something of the order of 30 miles (55 km). However, this "safety factor" enabled useful results to be obtained on several occasions with cable faults or damage, which would otherwise have rendered the equipment inoperative.

No quantitative data on polar radiation diagrams are available; it was reported that no blind, or partially blind, sectors were observed. Estimates based on other measurements suggest that the mast "shadow" for aerials, fitted as shown in Fig. 19, would be of the order of 4 db deep and that its effect would extend well beyond the limits of geometrical screening.

In general, operation of the equipment, once learnt, was found easy; "listening through" was consistently satisfactory; and no interference was observed to or from other equipment.

It was realized, while this equipment was being fitted, that the degree of complexity accepted in the transmitter in the quest for frequency stability and convenience of operation was unnecessarily great. A very much simplified version was built in the Laboratories in 1940 to provide a single communication channel for use in other work; it used the receiver described above. The whole system operated for about 4 months of intermittent service with no readjustment; the receiver was then found to be barely 0.2 Mc/s off tune.

This was, however, only one of many lessons learnt in the course of a project, which attempted much that had not been attempted before, and provided a legacy of knowledge and experience to contribute to the radar developments which were taking shape during its closing phases.

6. – Acknowledgments.

Among the many members of the staffs of the Experimental Department of H. M. Signal School (now Admiralty Signal Establishment), and of the General Electric Company, who contributed at various stages to the development of the equipment described in this paper it is particularly desired to mention:

Mr. G. Shearing, formerly Superintending Scientist in H. M. Signal School, whose advice and encouragement were especially valuable in the early stages of the work;

Mr. J. F. Coales, who was responsible for the project in H. M. Signal School during the period of experimental trials and subsequent development for production;

Mr. R. G. Mitchell and Mr. J. C. Dix who were successively responsible for the receiver work;

Mr. H. Archer-Thomson, Mr. E. F. Foreman, and Mr. C. Chilton, who were responsible for most of the engineering of the experimental and the development models, and who contributed much to the organization and execution of the various trials;

Mr. W. Carter of the G. E. C. Telephone Works, who made many valuable contributions to design during the preparations for production; and

Mr. R. E. Soper of Pirelli-General Cable Works, who was responsible for the development work on the cables and associated fittings.

Finally it is desired to pay tribute to Sir Charles Wright, formerly Director of Scientific Research, Admiralty, whose conviction of the future usefulness of very short radio waves to the Royal Navy led to the initiation of the work.

September, 1947.