SHORT ELECTRIC WAVES

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Abstract

Extension of electric wave spectrum to wave-length of 1.8 mm.—As a result of improved apparatus and technique, the electric wave spectrum has recently been extended two octaves nearer to the long wave limit of the heat spectrum. *Improved Hertzian oscillators* were made with pairs of tungsten cylinders 0.5 to 0.2 mm in diameter and 5 to 0.2 mm long, sealed into glass. Increased efficiency was obtained by use of jets of compressed air for the auxiliary gaps and of kerosene for the main gap. As the length of oscillator decreases from 10 to 0.4 mm, the ratio of fundamental wave-length to oscillator length increases from 2.7 to 4.8, making progress increasingly difficult. To measure the radiation, various *improved radiometer receivers* were developed. Receiving elements either of short lengths of 1 μ platinum wire or of narrow strips of platinum film deposited on thin mica were substituted for the usual black vanes. The sensitive systems were suspended by quartz fibers and weighed only $\frac{1}{2}$ to 1 mg. By proper choice and adjustment of the elements, the receiver can be made either selective or not. By direct test, the deflection was proved proportional to the incident energy. Mirrors and paraffin lenses were used in focussing the energy from the oscillator on the receiving element. *Wave-length measurements* were made with the aid of a Boltzmann divided mirror interferometer, and *energy-distribution curves* were obtained for various oscillators and receivers. To correct for the variations in the emission of the oscillator, readings were made, simultaneously, of the total emission with a check receiver, and of the radiation of a particular wave-length. On account of the high damping of the oscillator, the curves obtained show the predominant influence of the fundamental frequency of the receiver but also maxima when partials of the oscillator coincide with one or other of the partials of the receiver. The shortest fundamental wave-length obtained is 1.8 mm, two octaves shorter than the shortest previously measured, 7 mm. An upper partial of 0.8 mm was also observed. Greater homogeneity was secured by use of a *reflecting echelon*, $\frac{1}{2}\lambda$ between treads, since it reflects selectively. A simple mounting permitting easy adjustment is described. Two such echelons with steps at right angles give, under suitable conditions, a fair approximation to monochromatic radiation. By use of such echelons it should be possible to isolate upper partials still shorter than those so far measured.

THERE is doubtless little need of any further experimental proof of the essential identity between heat waves and electric waves, yet for the sake of completeness, further effort to bridge the existing gap between these two spectra seems warranted. Moreover, the optical properties of many substances, of which water is a notable example, undergo such unusual changes in crossing this unknown region as to lend some theoretical importance to its further exploration.

An interval of more than 15 octaves separated the highest frequency of Hertz's shortest electric waves from the frequency of Langley's longest heat waves. By the experiments of Righi,[1] Lèbedew,[2] Lampa,[3] and Möbius [4] on the one side and by those of Rubens with Nichols,[5] Wood,[6] and Von Baeyer [7] on the other, this unexplored interval had been progressively reduced to 4 or 5 octaves.

The precise extent of the conquered territory on the electric wave side is less certain and definite than the outer known limits of the heat spectrum. The difficulties which beset the explorer in the two fields differ in many details but agree in one most important respect. Further progress in both domains awaits the development of more sensitive and dependable receiving apparatus. However, the apparatus and technique of short electric wave experiments has been less extensively, methodically, and painstakingly developed than the instruments and methods employed in the infra-red spectrum. For this reason, if for no other, an attack on the problem of bringing the two spectra together seems more promising if made on the electric wave side.

The experiments described in this paper were undertaken, therefore, in the hope that by devising better instruments and better and more accurate methods of experimentation with short electric waves, further progress might be made in narrowing the still unexplored region between the two spectra and in making the results of future short electric wave experiments more strictly quantitative and trustworthy.

Source of Radiation

A very small Hertz doublet immersed in kerosene was used as a source. To adapt this form of oscillator to short wave emission a number of departures from earlier practice were made. Instead of using small cylinders of platinum for the two halves of the doublet, cylinders of tungsten were substituted and found in use to wear away more evenly and less rapidly than platinum.

For the different oscillators employed in the present experiments, tungsten cylinders, varying in length from several millimeters to 0.2 mm and in diameter from 0.5 mm to 0.2 mm, were sealed into the closed ends of tubes of hard glass having the same expansion coefficient as the

[1] Righi, Mem. del R. Acad. dei Sc. del Inst. di Bologna, v. 4, 1894.

[2] Lebedew, Wied. Ann. **56**, 1, 1895.

[3] Lampa, Wiener Ber. **105**, 587 and 1049, 1896; **104**, 1179, 1895.

[4] Möbius, Ann. der Phys. **62**, 293, 1920.

[5] H. Rubens and E. F. Nichols, Phys. Rev. **4**, 314, 1897; **5**, 98 and 152, 1897; Ann. der Phys. **60**, 418, 1897.

[6] H. Rubens and R. W. Wood, Phil. Mag. **21**, 249, 1911.

[7] H. Rubens and O. Von Baeyer, Phil. Mag. **21**, 689, 1911.

metal. These tubes T and T_1 were mounted, as shown in Fig. 1, in a holder A, hinged at H. The length of the spark gap between the tungsten cylinders c and c_1 was of the order of 0.01 mm and was adjustable to the

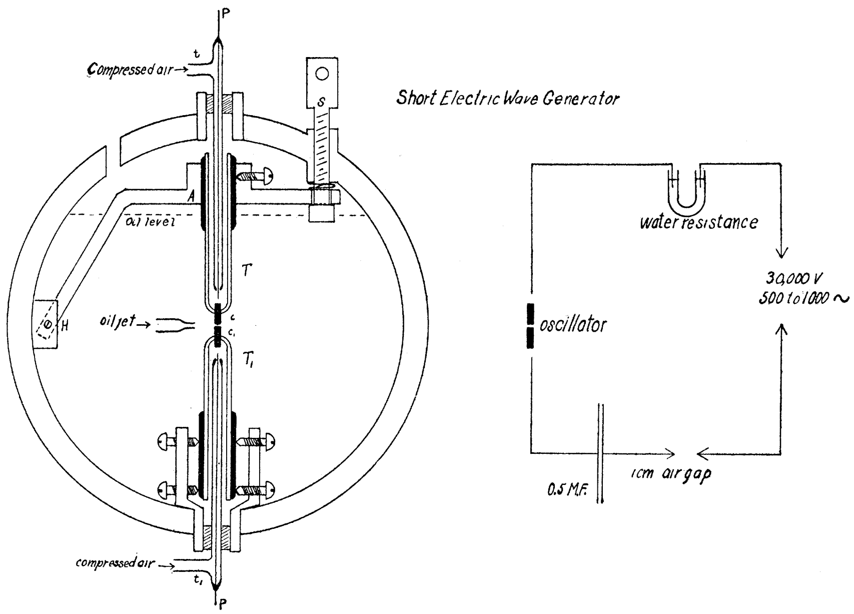

Fig. 1. Sketch of oscillator.

requisite precision by the micrometer screw S. In the open ends of the tubes T and T_1, inner tubes t and t_1 were introduced carrying wires from the high potential circuit P. The inner ends of these wires were brought near the outer ends of the tungsten doublet and separated from them only by short spark gaps in air. Side openings in the inner tubes admitted a stream of compressed air which served a threefold purpose. It more quickly de-ionized the air gaps after each discharge; it cooled the tungsten glass seals; and by a slight excess of pressure, it prevented kerosene from leaking into the air gaps through any imperfections in the tungsten glass seals.

The doublet was mounted at the center of curvature of a concave spherical mirror in a cylindrical brass case containing kerosene (see Fig. 2). The radiation issued through a circular mica-covered window, 4 cm in diameter, in the front of the oscillator box, and was formed into a parallel beam by a double convex paraffin lens.

As the intensity of radiation from the oscillator depends on the effective frequency of excitation which in turn is limited by the time required to restore the oil insulation in the main spark gap after each discharge, two methods were tried for shortening this period.

First, a kerosene jet from a centrifugal pump driven by an air turbine was directed toward the spark gap to hasten the clearing away of gas bubbles formed by the spark. The jet nozzle is indicated in Fig. 1, and the air turbine is seen at the left on top of the oscillator box in Fig. 2. Although with the jet in operation it is possible to increase the effective frequency of discharge by about fifty per cent, recourse to it has proved necessary only when the smallest oscillators were used.

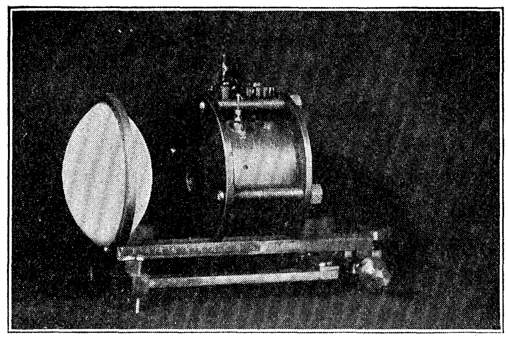

Fig. 2. Photo of oscillator.

Second, the kerosene in the oscillator case was put under pressure varying from 0.1 to 4 atmospheres. Intensity of radiation increased rapidly with pressure from 0.1 to 1 atmosphere and from there on more slowly, reaching a maximum at about 3 atmospheres, at which pressure an increase in intensity of about fifty per cent over that at one atmosphere was observed. The maximum at 3 atmospheres is probably an individual characteristic of the apparatus used, for beyond this pressure the available potential proved insufficient to break down the kerosene insulation at the spark gap for every excitation of the coil, hence the action became somewhat irregular. Although increased pressure thus gives a second means of increasing radiant intensity, the oscillator, for greater convenience, has ordinarily been operated at atmospheric pressure.

In addition to the oscillator, the high potential circuit included the secondary of an induction coil giving 30,000 volts, a water resistance, a spark gap, and a condenser, all in series. The primary circuit of the induction coil included a rotating mechanical make-and-break from which any frequency of interruption up to 1000 per second was readily obtained. The primary circuit also included an automatic time switch permitting the operation of the coil for any chosen time interval, thus affording a convenient means of accurately controlling the "exposure times" used in making observations.

The Receiver

The possibility of developing different types of metallic systems suspended by quartz fibers, as new forms of sensitive electric wave receivers, has been discussed elsewhere by one of the present writers.[8] Of this class, the radiometer type of receiver has been most worked on. This form was first mentioned by Hull who mounted a radiometer vane facing a high resistance section in the middle of a linear receiving resonator. Deflections of the radiometer vane were produced by the heat generated in the resonator resistance by electric oscillations.

Later Webb [9] mounted a linear resonator like Hull's, directly on a radiometer suspension. To make the radiometric impulse unilateral, a thin mica shield was mounted behind the high resistance portion of the resonator. Webb also mounted uniform strips of the thinnest obtainable metal foils, shielded on one side by mica, as radiometer vanes.

Webb's experiments served as the point of departure in designing a radiometric receiver for the present work. In changing from metal foils to light deposits of platinum on the thinnest mica, a marked increase in sensitiveness was obtained, and still further and more striking increases followed the substitution of mounted strands of platinum wire of the order of 1 μ in diameter. In all thermal electric wave receivers, the same problem is met. If the resistance is too high, the radiation sweeps past it; if too low, the radiation is almost wholly reflected or re-emitted. In neither case is the maximum energy absorbed. The best absorption resistances so far obtained have been reached through carefully controlled, cut and try experiments.

The forms of radiometer vanes tested in the present experiments have been various, but the methods of vane shielding and mounting have been similar. A typical suspension is shown at a, Fig. 3, in which the rotation axis q, a straight, fine-drawn rod of quartz or hard glass about 5 cm long and from 0.05 to 0.02 mm in diameter, hangs by a quartz fiber f. A silvered mirror m of microscope cover glass, 0.5 to 1 mm high by 1 mm wide and about .07 mm thick, is attached to q, to which the fine-drawn glass cross arms c_1 and c_2, carrying thin mica shields v_1 and v_2, (0.2×1) to (0.5×10) mm, are also made fast. The distance between the outside edges of v_1 and v_2 varied from 1 to 2 mm in different suspensions. Just in front of, but not touching v_1, and just behind, but not touching v_2, were mounted the various resonator heating elements. When these are warmed by absorption of electric radiation, the moments of the radiometric forces on both vanes lie in the same direction.

[8] E. F. Nichols, International Electrical Congress, St. Louis, 1904.

[9] H. W. Webb, Phys. Rev. **30**, 192, 1910.

All joints shown in Fig. 3 were made with minute bits of fused shellac, and the total weight of each of the various types of suspension was less than a milligram, and in some instances not more than one half milligram. It was by thus scaling down the linear dimensions and weight of the present suspension beyond those of earlier radiometers that the greater part of the greatly increased sensitivity was obtained.

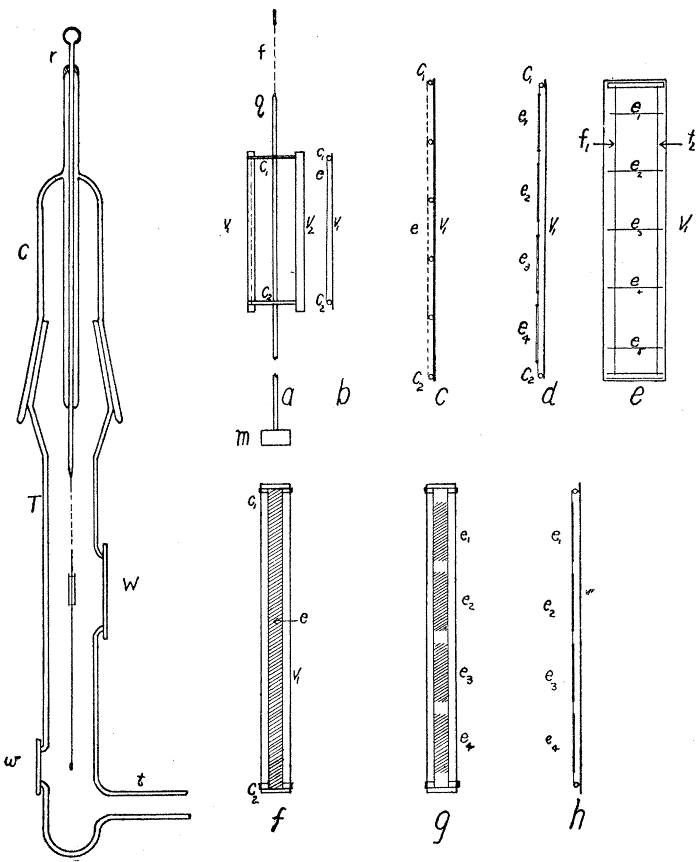

Fig. 3. Receiver types.

During tests, suspensions were mounted axially in a glass tube *T*, Fig. 3. The best working conditions were met by a tube of about 15 mm diameter. In such a housing, the mica walls, often set opposite radiometer vanes to increase the sensitiveness, are unnecessary. The tube *T* bears a ground joint at the top fitted by a cap *C* carrying a drawn down axial rod *r* to which the upper end of the quartz fiber *f*, bearing the suspension, is attached. By turning the cap *C* on the ground joint, the orientation of the suspension can be varied at will. T has two side window openings W and w. The former, covered by an ebonite plate, admits the beam of electric waves; the latter is covered by plate glass, and through it the deflections of the suspended system were read with telescope and scale. A side tube t connects the receiver to a mercury pump. The receivers showed maximum sensitiveness for gas pressures of approximately .05 mm of mercury. In pumping out the receiver a black vaned torsion radiometer included in the same vacuum line and deflected by the rays from a constant tungsten lamp, was used as a rough pressure gauge. Deflections of this auxiliary radiometer were indicated by a light spot projected on a scale, and pumping was stopped when the radiometer deflection reached a maximum and turned back.

To guard against disturbances arising from stray radiation or other temperature differences, the receiver case was surrounded by cotton and packed in a thick-walled brass tube provided with the necessary window openings.

The resonator heating elements so far tried as receiver vanes fall into two general classes, (1) those made of fine Wollaston wire of about 1 μ diameter, and (2) those made by depositing light metal coatings on thin mica strips or quartz fibers by the method of evaporation or cathode discharge at low pressures.

Fig. 3*b* shows an enlarged receiver vane, edge on. The heater element e, of platinum wire 1 μ in diameter, is stretched between the cross rods c_1, c_2 in front of the thin mica shield v_1. This resonator had a fundamental period corresponding to its total length, and a complete series of upper partials.

The vane in Fig. 3*c* is similar in type to that in Fig. 3*b* except for a number of short glass rods used as bridges between c_1 and c_2. Over these bridges a continuous length of 1 μ wire could be stretched or a series of short discontinuous lengths reaching only from one bridge to the next. In the first instance, a fundamental was obtained similar to that for Fig. 3*b*, but with an accented upper partial of a frequency dependent upon the distance between bridges and also upon the added capacities thus introduced. For the discontinuous lengths, the fundamental corresponding to the total vane length disappeared altogether, of course, leaving a receiver tuned to the shorter wave-length.

In the arrangement of Fig. 3*d*, a quartz fiber is stretched between the cross arms c_1, c_2 in front of the shield v_1. To this fiber, short lengths of 1 μ wire e_1, e_2, e_3, etc., are attached. For the same dimensions, this receiver corresponds to a shorter wave-length resonance than the receiver 3*c*, because of smaller end capacities, and it is also more sharply selective because less damped.

In Fig. 3*e*, the receiver vane is shown face on. Two quartz fibers f_1, f_2 are stretched in front of the mica shield v_1, and short sections of 1 μ wire e_1, e_2, e_3, etc., are stretched from one fiber across to the other like the rungs of a ladder. This is the only receiver used in which the electric vector is horizontal instead of vertical.

Receiver vanes of the second class with resonator heating elements made of light metallic deposits were of the three principal forms shown in Figs. 3*f*, 3*g*, and 3*h*. In Fig. 3*f* a long, narrow, uniformly coated platinized strip *e* of very thin mica was attached to the cross rods c_1, c_2 in front of the mica shield v_1. In natural frequency and general characteristics, this mounting is comparable with that shown in Fig. 3*b*. Fig. 3*g* shows a variation from Fig. 3*f* produced by placing small bars across the thin mica strip while the metal coating was being deposited. The shadows of the bars divide the strip into rectangular fields e_1, e_2, e_3, etc. The resonance frequencies of these elements were often erratic, due probably to the fact that the shadowed spaces, though clear in appearance, were not invariably non-conducting. The results showed resonance frequencies corresponding to the dimensions of the individual fields, and additional lower frequencies corresponding probably to several fields acting as one. A variant on this type of resonance heater was constructed by cutting a uniform strip such as *e*, Fig. 3*f*, into short lengths and attaching these separately to another mica sheet. The frequencies thus obtained corresponded to the dimensions of the metal-coated rectangles, and there was no response to longer waves.

The vane shown in Fig. 3*h* has heater elements e_1, e_2, e_3, etc., made by depositing regional metal coatings on a quartz fiber. If care is taken in the process to effectively shield the quartz fiber between metallized sections and thus secure adequate insulation, results comparable to those with the heater elements e_1, e_2, e_3, etc., in Fig. 3*d* can be obtained.

When a receiver is first assembled, the suspension takes up some position usually quite independent of the position of the torsion cap. The introduction of a small quantity of radioactive material hastens the dissipation of any accidental static charges responsible for such disturbances so that after a brief interval the suspension readily responds to the torsion cap even with the finest fibers. In the present experiments the writers are indebted to Professor A. Kovarik of Yale, who very kindly supplied several polonium deposits on copper disks, which were placed in the various receivers; and later Dr. E. Karrer of the Applied Science Laboratory, National Lamp Works, kindly loaned some small tubes of radioactive material for the same use. A fiber was usually chosen which after a deflection brought the system back to zero in about twenty seconds. For exposures of from one fifth to one and a half seconds the size of the deflections obtained depends but little on the torsion of the fiber and almost wholly upon the work done by the system against viscosity in moving through the residual gas.

To test the strict proportionality of receiver deflections to incident energy for this new type of electric wave receiver, the following experiment based on the polarizing action of wire gratings for electric waves was tried. The oscillator emitting a plane polarized beam was set with electric vector vertical. A receiver with vertical resonators of the type shown in Fig. 3*b* was placed in the beam from the oscillator. When a wire grating, with grating space small compared to the wave-length of

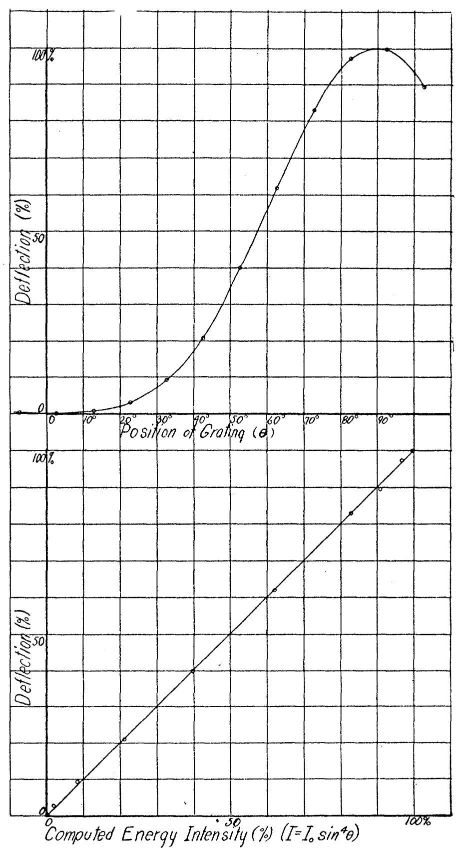

Fig. 4. Polarizing grating data.

the incident radiation, is placed between oscillator and receiver and rotated in a plane perpendicular to the line joining them, its polarizing action is, like that of a nicol introduced between polarizer and analyzer, set parallel. By analogy, therefore, in our arrangement of oscillator, grating, and receiver, the grating transmission in different orientations should equal the product of incident energy by the fourth power of the sine of the angle between the direction of the grating wires and the vertical. For a wave-length of 18 mm and a grating of brass wires, 0.1 mm in diameter and spaced 32 to the centimeter, observed deflections and computed transmissions were proportional to within one per cent as will be seen from Fig. 4.

Wave-Length Measurements

The resonance absorption of all the various receiving elements tested was strongly selective and usually showed a pronounced absorption for a fundamental frequency and a diminishing selective absorption for a complete series of upper partials. The fundamental absorption wave-lengths of the different receivers employed ranged from 4 to 30 mm.

When oscillator and receiver are approximately in resonance, quite satisfactory wave-length measurements can be made with the familiar Boltzmann divided mirrors. A photograph of the Boltzmann interferometer employed is shown in Fig. 5. The mirror plates are of brass

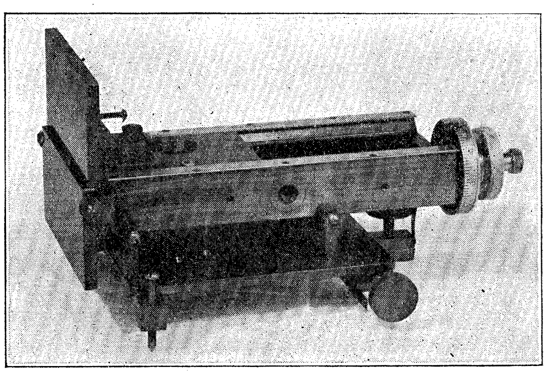

Fig. 5. Photo of Boltzmann interferometer.

($5 \times 10 \times 0.6$ cm), with plane surfaces. The lower half mirror is stationary; the upper half, mounted on a micrometer-screw slide, can be moved measured distances backward or forward. The mirror planes can be set accurately parallel by means of slow motion adjustments. Either mirror can also be turned about a vertical axis to deflect its beam to one side and again swung back to parallelism without loss of adjustment, thus making it easy at any time to test the energy equality of the two beams.

In Fig. 6 a diagram is shown of the arrangement of apparatus for wave-length measurements. The oscillator at G is at the center of curvature of a spherical mirror m and in the principal focus of a double convex paraffin lens L_1. L_2 and L_3 denote equal paraffin lenses of 12 cm diameter and 8 cm focal length. A plane mirror is placed at A, the

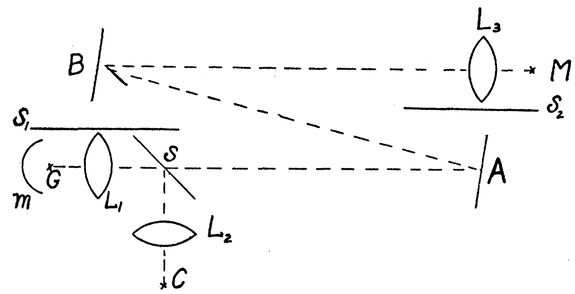

Fig. 6. Diagram for wave-length measurements.

interferometer at B, and the main receiver in the principal focus of L_3 at M. A portion of the energy of the parallel beam from the oscillator is reflected by a sheet of glass, of ebonite, or of thin cardboard at S, at right angles to the lens L_2, and is focused on a second or check receiver. The metal screens S_1 and S_2 were necessary only for wave-lengths greater than one centimeter.

Lenses and mirrors were adjusted as follows: After the lenses were cast and turned to fit a given template and before removal from the lathe, a two mm hole was drilled along the axis of rotation of each lens. A frame bearing two properly centered diaphragms, lighted from behind, was fitted to replace the oscillator case on the optical bench. The light pencil directed by these diaphragms defined the optic axes of the system; after passing through the hole in L_1, it was reflected in succession from mirrors at A and B, then passed through L_3 and fell upon the receiver at M. The mirrors A and B and the optical bench carrying the oscillator case and lens L_1 are provided with micrometer adjustments for rotation about vertical and horizontal axes. Lenses L_2 and L_3 are provided with slow motion vertical and horizontal adjustments. The adjustment obtained by using the pencil of light rays has been found to agree with that subsequently obtained by the more tedious method of experimental trial and error. Slightly tilting the common plane of the interferometer mirrors affords a convenient method for obtaining energy equality between the two beams reflected from the Boltzmann interferometer and brought to focus at M.

A Hertzian oscillator, especially a short wave oscillator, because of its rapid wearing away and constant need of readjustment, is very erratic and unsteady in action. It can in no sense be called either a constant source of radiation or even a uniformly varying source. Consequently the experimental procedure followed by earlier short wave experimenters has led at best to results which were only in the roughest sense quantitative. In the present experiments, a check was kept at all times on the emission of the oscillator by the "check receiver" mentioned above. In any given series of observations, the main and check receivers were made of nearly identical construction. Thus for every excitation of the oscillator, the deflections of both main and check receivers were recorded. The ratio of these two deflections gives a quantity free from any error due to variable emission of the oscillator. Since nearly equal deflections of the main and check receivers offer the best conditions for accuracy, the material of the reflector at S was so chosen as to secure this equality.

In the interpretation of electric wave interference curves, it is important to know something of the relative influence on curve form of the fundamental and upper partials of the oscillator and of the receiver. Fig. 7 shows a series of interference curves obtained by using a single receiver

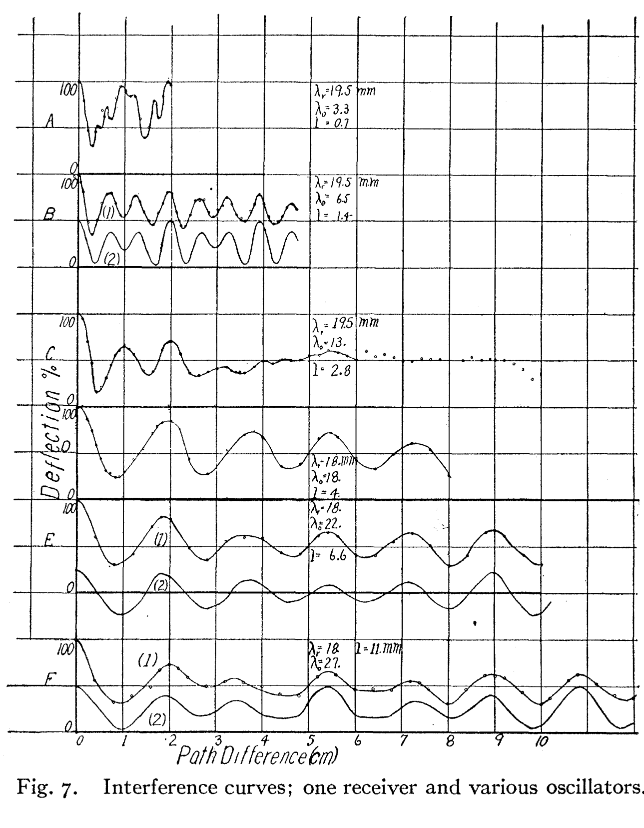

Fig. 7. Interference curves; one receiver and various oscillators.

and a series of different oscillators. The overall length l of the oscillator used and its approximate fundamental wave-length λ_0 are given with each curve. The receiver was of the type shown at a, Fig. 3, with vanes made of 1 μ platinum wire 5.5 mm in length, of which about 0.3 mm at each end was embedded in shellac. Its fundamental wave-length λ_r, measured from the different curves, ranges between 18 and 20 mm.

Curve A, Fig. 7.—The curve for this combination of oscillator and receiver exhibits six maxima between zero and a path difference of 19 mm; thus λ_0 equals $\lambda_r/6$, or the fifth upper partial of the receiver. The curve form also shows the presence of the first upper partial and fundamental of the receiver.

Curve B_1, Fig. 7, shows three maxima and three minima between the path difference zero and 19.5 mm. Thus as $\lambda_0 = \lambda_r/3$, the oscillator fundamental falls in step with the second upper partial of the receiver. Analysis of this curve, damping neglected, yields the equation

$$Y = \tfrac{1}{3} \cos (2\pi x/\tfrac{1}{2}\lambda_r) + \tfrac{2}{3} \cos (2\pi x/\tfrac{1}{3}\lambda_r),$$

showing that the first upper partial of the receiver is also present with roughly one half the intensity of the second. A plot of this equation appears as B_2, Fig. 7.

Curve C, Fig. 7, shows the fundamental and first upper partial of the receiver. There is no clear indication of any maximum due to the fundamental of the oscillator. The rapid flattening out of the curve is doubtless attributable to the complete disagreement between the fundamental wave-lengths and upper partials of oscillator and receiver.

Curve D, Fig. 7.—The oscillator fundamental, $\lambda_0 = 18$ mm approximately, was near enough to λ_r to give a regular curve of simple form and sustained amplitude, showing the receiver to be in fair resonance with the oscillator.

Curve E_1, Fig. 7.—The fundamental of the oscillator with which this curve was made was somewhat longer than that of the receiver but yet near enough to give a curve of well-sustained amplitude though not altogether simple in form. Curve E_2, Fig. 7, is drawn from equation $Y = \tfrac{2}{3} \cos (2\pi x/\lambda_r) + \tfrac{1}{3} \cos (2\pi x/\lambda_0)$, where $\lambda_0 = 21.6$ mm and $\lambda_r = 18$ mm, which gives a close enough match with E_1 to show (1) that the wave-lengths assigned in this instance to oscillator and receiver are accurately chosen and (2) that the receiver has roughly twice as much effect upon the form of the curve as the oscillator.

Curve F_1, Fig. 7.—Here $\lambda_0 = 3\lambda_r/2$ nearly, and the amplitude is well sustained and yields a curve form of unusual interest. Curve F_2 is drawn from $Y = \tfrac{2}{3} \cos (2\pi x/\lambda_r) + \tfrac{1}{3} \cos (2\pi x/\lambda_0)$, where $\lambda_r = 18$ mm and $\lambda_0 = 27$ mm, which, damping neglected, affords a very close reproduction of F_1.

Irrespective of the different dimensions and characteristics of the oscillators used, all the interference curves in Fig. 7 show a strong maximum at a path difference of about 19 mm or λ_r, indicating plainly that the receiver, because it is less damped than the oscillator, exerts the predominant influence upon the form of the interference curves and upon the fundamental wave-lengths and upper partials thus measured.

Consideration of Fig. 7 and of the foregoing discussion shows that interference curves of simple and regular form and of sustained amplitude are obtained only when the fundamental periods of oscillator and receiver fall close together or when the oscillator fundamental is in close agreement with the first or second upper partial of the receiver. It thus appears that the radiation from the oscillator is highly damped and though not aperiodic may be thought of as a pulse or, even more accurately, as a

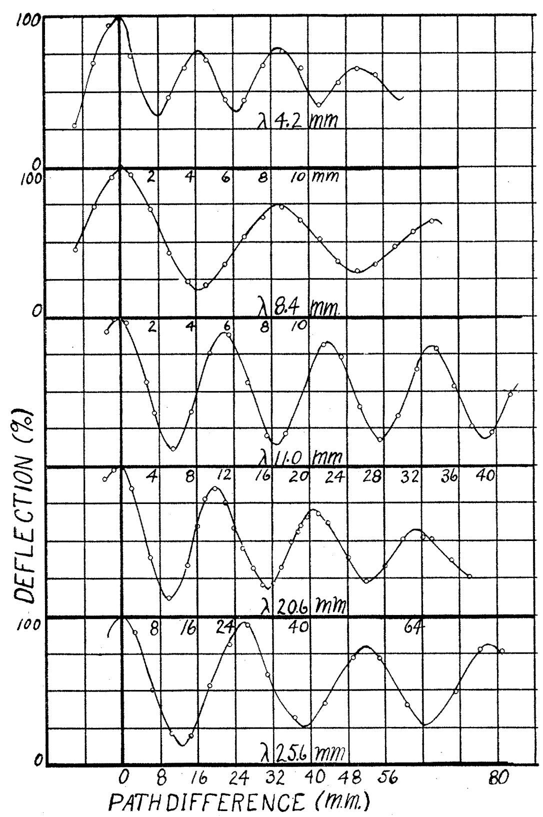

Fig. 8. Set of curves, λ 4.2 to λ 27.

very short wave train with from 60 to 80 per cent of the energy concentrated in the first half wave-length. Upon reflection from the two halves of the interferometer mirror, each pulse is divided into two parts, one following the other by a known time interval. When the time separation of the two pulses is equal to or a small multiple of a natural period of the receiver, we may expect a maximum response. Were the receiver heavily enough damped to be aperiodic, the interference curve would give a measure of the wave-length of the unmodified radiation of the oscillator. Since the receiver is but slightly damped and the oscillator not altogether aperiodic, the interference curve obtained is a compromise of the two effects, in which the receiver is much the larger factor.

These considerations find further illustration in Fig. 8. Curves *A* and *B* were taken with different oscillators but with the same receiver, the fundamental wave-length of which was $\lambda_r = 8.4$ mm. In curve *A*, the fundamental wave-length of the oscillator is 4.2 mm, corresponding to the first upper partial of the receiver. In the remaining curves *C*, *D*, and *E*, the fundamentals of oscillator and receiver were in close agreement.

The observations from which curve *A* is plotted are given in Table I.

TABLE I

Int. mirror setting	Main receiver (M)	Check receiver (C)	$\frac{M}{C}$	Deflection, per cent
8.5 mm	58 mm	118 mm	.49	60
8.	40	76	.53	65
7.5	36	78	.46	56
7.	26	78	.33	40
6.5	53	93	.58	71
6.	34	56	.61	74
6.	96	147	.65	79
5.5	55	93	.59	72
5.	37	103	.36	44
4.5	32	97	.33	40
4.5*	47	126	.37	45
4.	59	103	.57	70
4.*	44	72	.61	74
3.5*	66	115	.57	70
3.	45	120	.37	45
3.*	41	109	.38	46
2.5	32	123	.26	32
2.5*	29	120	.24	29
2.	76	127	.60	73
1.5	82	100	.82	100
1.	55	99	.56	68
0.5	26	119	.22	27

They show something of the sensitiveness and behavior of the receiver and the general character of the work with short electric waves, and thus afford a basis for judging the results obtained. Column 1 gives the scale readings of the movable upper interferometer mirror plotted as abscissas in curve *A*; column 2, the corresponding deflections of the main receiver; and column 3, the deflections of the check receiver. Column 4 shows the ratio, and column 5 the so-called deflection percentages plotted as ordinates in the curve. The starred values constitute a second series of interferometer settings.

The arrangement of apparatus used is shown in Fig. 6. The total length of path from oscillator to main receiver, including two reflections, was 180 cm. By means of the time switch, previously referred to, the oscillator was operated for one half second for each deflection. If we take the average of the sum of the deflections of the main and check receivers for maximum points in the interference curve, we get the equivalent of 200 scale divisions on a meter distant scale. The corresponding combined deflection for a 1.5 second exposure was roughly 600 divisions, a remarkably high degree of receiver sensitiveness for waves of this length. The irregular emission of the oscillator is plainly seen in the varying numbers of column 3. Were the oscillator a constant source, these check receiver deflections should have shown no variation. The necessity of using a check receiver for quantitative work is thus evident, and yet, so far as we know, this is the first instance of its use in short electric wave experiments, *i.e.*, with waves less than 4 or 5 cm long.

Upper partials of short wave-length.—Upon continued use, the inner ends of the oscillator doublet at the oil gap become badly pitted and sometimes develop notches or "teeth." This tendency is more marked for platinum than for tungsten electrodes. With increased pitting and "teething" the normal oscillations become less sustained, and the interference curves show the presence of radiation of much shorter wave-length though the curves are seldom of regular pattern. Möbius (4) has thus obtained interference curves which suggest the presence of radiation of a wave-length hardly more than one per cent of the fundamental of his oscillator.

Curve *A*, Fig. 9, was taken with an oscillator of fundamental wave-length about 4 mm operated with a long spark gap between badly pitted platinum electrodes. The receiver elements were thin platinum deposits on mica of type *e*, Fig. 3, and though in action the receiver showed high resistance damping, it had a fundamental wave-length of about 8 mm. The deep minimum and succeeding maximum are evidently due to the receiver. Interferometer settings were made near together for only the first two millimeters displacement. If from the observed deflections the function $60 + 40 \cos (2\pi x/4)$ is subtracted, curve *B*, Fig. 9, is obtained, which plainly indicates the presence of a component of wave-length 0.8 mm. As $\lambda_0/5 = \lambda_r/10 = 0.8$ mm, we apparently have the fourth upper partial of the oscillator falling in with the ninth upper partial of the receiver.

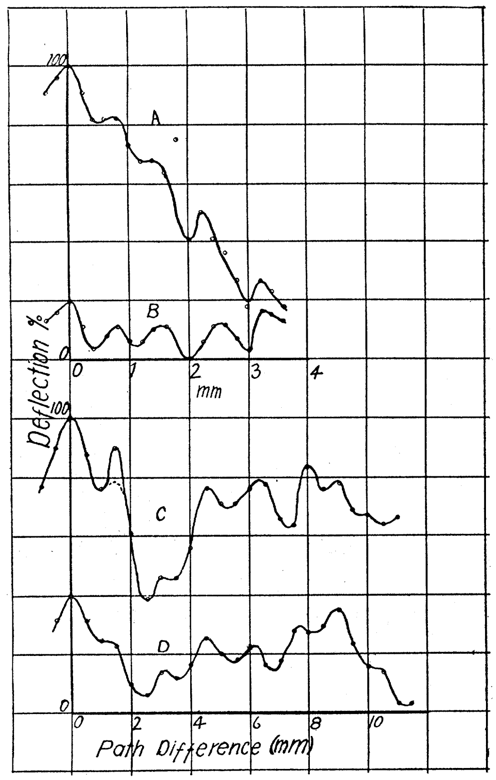

Fig. 9. Harmonics.

For Curve *C*, Fig. 9, the receiver elements, of 1 μ platinum wire, were of type *a*, Fig. 3, and the fundamental wave-length was 7.5 mm. The fundamental of the oscillator was 4.5 mm, the tungsten electrodes were badly worn, and the spark gap long. Emission had fallen to 20 per cent of its initial intensity. Curve *D*, Fig. 9, is the sum of three harmonic curves corresponding to the equation

$$Y = 2/5 \cos (4\pi x/7.5) + 2/5 \cos (4\pi x/4.5) + 1/5 \cos (4\pi x/1.5).$$

Its resemblance to Curve *C* is sufficiently close to show three components 7.5, 4.5, and 1.5 mm; the first is the fundamental of the receiver, the second that of the oscillator, and the third is formed by the second upper partial of the oscillator falling in with the fourth upper partial of the receiver.

A reflecting echelon.—The degree of damping which determines the form of the pulse or short wave train for electric waves in air has been studied by Hull,[10] Bartenstein,[11] and Ives.[12] The results obtained by these investigators agree as to the general nature of the radiation; but because of the different forms of oscillators used by them, and because the influence of the receiver upon the interference curve was not in all cases satisfactorily eliminated, their results show a wide variation in the degree of damping reported. As a further means for analyzing the wave form and content of the emission of very short wave oscillators, a reflecting echelon grating was constructed of eight carefully machined and polished brass blocks bearing against a strip of plate glass as shown in Fig. 10. The inclination of this glass plate and with it the equivalent

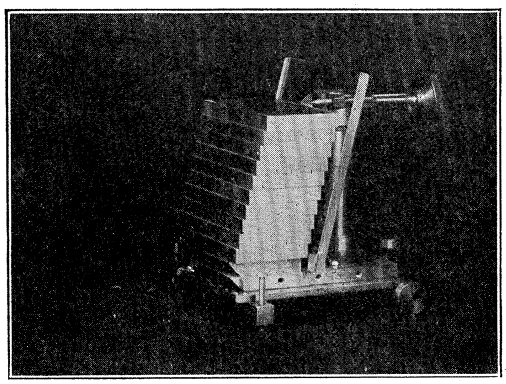

Fig. 10. Photo of echelon.

grating space or tread of the steps could be varied by means of a micrometer screw shown in the figure. In use this echelon is placed in the optical path at B, Fig. 6. If the tread of the steps is made equal to half the fundamental wave-length of the incident radiation, the original pulse or short wave train is divided into eight trains one following another at intervals of one oscillator cycle. For purposes of illustration, the damping is assumed to be such that the amplitude falls to 1 per cent of its initial value in four cycles. The calculated resultant wave form obtained by adding the displaced 8 wave trains is shown in Fig. 11. The echelon thus serves to isolate the fundamental wave emitted by the oscillator and to render it more nearly monochromatic. If a receiver with a very much longer fundamental than that of the oscillator is used,

[10] G. F. Hull, Phys. Rev. 5, 231–46, 1897.
[11] Bartenstein, Ann. der Phys. 29, 201, 1909.
[12] Ives, Phys. Rev. 31, 185, 1910.

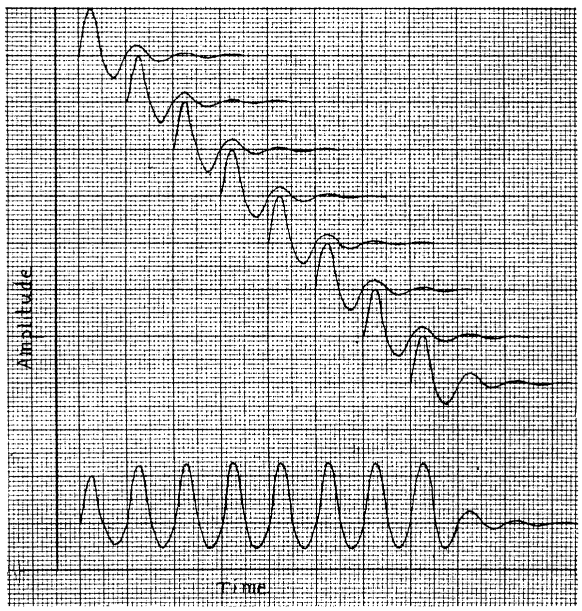

Fig. 11. Addition of pulses.

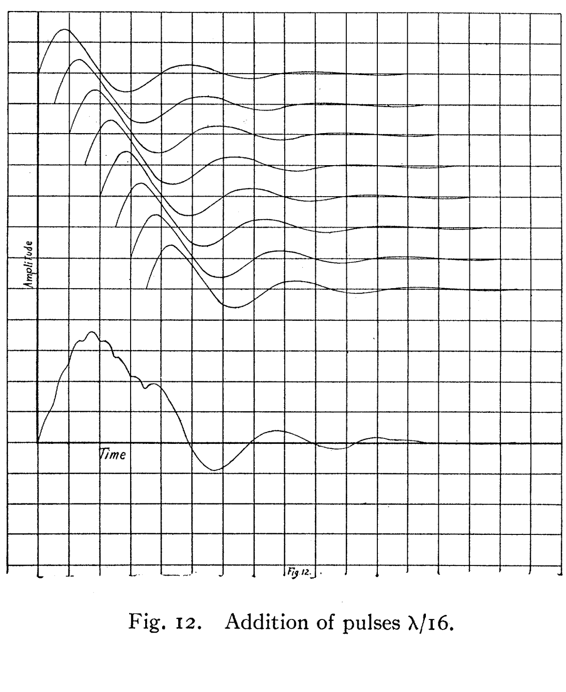

Fig. 12. Addition of pulses λ/16.

and the tread of the echelon is set for a path difference equal to the fundamental of the receiver, the result obtained will correspond to the characteristics of the receiver, irrespective of the characteristics of the oscillator. In this way it is possible to get a clear regular interference curve corresponding to the fundamental of the receiver even when no radiation anywhere near it in wave-length exists in the emission of the oscillator. The wave-length thus obtained is therefore wholly spurious in that it is manufactured by the echelon and receiver and is not emitted by the oscillator. While it is thus possible to get almost any wave-length to which the receiver responds, which is longer than that emitted by the oscillator, it is not practicable by use of the echelon to get waves very much shorter than the fundamental emission of the oscillator and its accented upper partials. Fig. 12 shows the computed resultant wave train due to setting the echelon tread at 1/16 of the fundamental wave-length of the oscillator. In it the fundamental of the oscillator appears as a ground wave and, superimposed upon it, are ripples 1/8 as long as the fundamental.

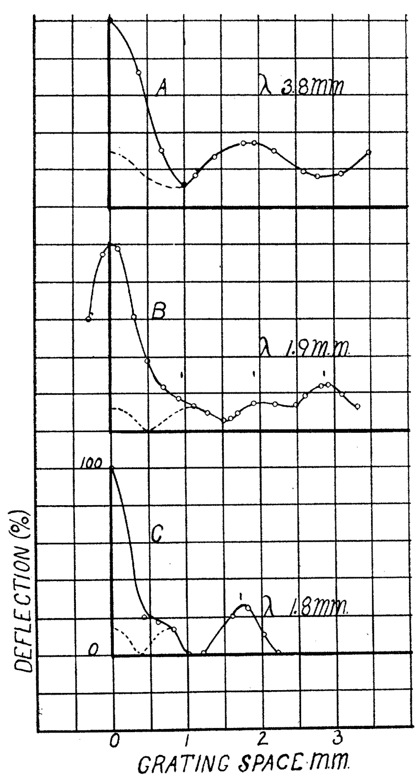

Fig. 13. Step curves.

The echelon method has been used to measure the fundamental wave-lengths and to analyze the radiation of a number of oscillators. In these experiments the receiver employed is of type *C*, Fig. 3, consisting of five parallel strands of 1 μ platinum wire. The various oscillator doublets employed consisted of tungsten cylinders, the smallest of which was 0.2 mm in diameter and 0.2 mm long. These were embedded in the glass tube ends for only about one half their length. The measured wave-lengths of curves *A*, *B*, and *C*, Fig. 13, were 3.8, 1.9, and 1.8 mm, respectively. Curve *B* was carried out to the third order. That a third maximum appears indicates that the radiation is less damped than that previously assumed and shown in Fig. 11.

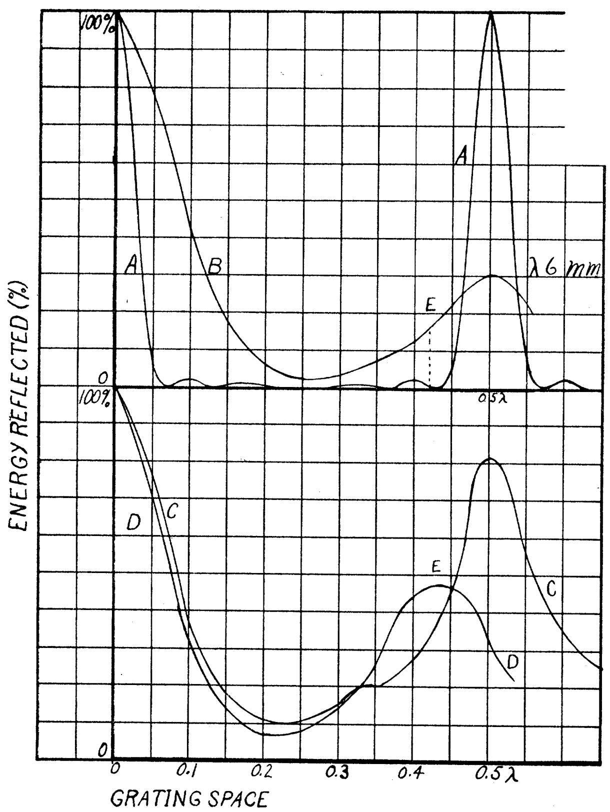

Fig. 14. Analysis of radiation (1) with echelon; (2) with crossed echelons.

To get higher resolving power for further analysis of the oscillator emission, a second echelon was constructed and the two used in series, the first placed at *A*, Fig. 6, with steps vertical, and the second at *B*, with steps horizontal. The width of tread of the first was set equal to half the fundamental wave-length of the oscillator λ_0, obtained from the position of the maximum in curve B, Fig. 14. The tread width of the second echelon was then varied continuously and curve C, Fig. 14, taken. The first maximum of curve C rises to within 80 per cent of the value of the first maximum of curve A computed for monochromatic radiation, thus showing an unexpected degree of homogeneity. The tread of the steps of the first echelon was then set for a width equal to $0.85\lambda_0/2$, requiring a maximum of the first order to fall at E. The tread width of the second echelon was then varied and curve D, Fig. 14, taken. The first maximum falls at the required place and rises to about 45 per cent of the theoretical maximum in curve A. This shows the influence of the first echelon upon the incident radiation, although after leaving the echelon, the radiation is less homogeneous in this case than in Fig. 14*c*. The procedure illustrated in Figs. 14*c* and 14*d* shows that the crossed echelons may be used to obtain radiation of wave-length somewhat less than the fundamental of the oscillator employed. The echelon principle also promises substantial assistance in the further difficult progress towards shorter waves, by making possible the singling out of higher upper partials from the complex emission of the oscillator. It is easier to build radiometric receivers tuned for very short waves than to construct oscillators to correspond. Hence the echelon together with very short tuned receivers offers the best arrangement so far realized for bringing the electric wave spectrum and the heat spectrum together.

The difficulty of building oscillators for very short electric waves lies not only in being able to handle and seal into glass such minute metal cylinders, but even more in the fact that the ratio of the fundamental wave-length of an oscillator to its total length is a ratio which for waves less than one centimeter increases rapidly as we go to higher and higher

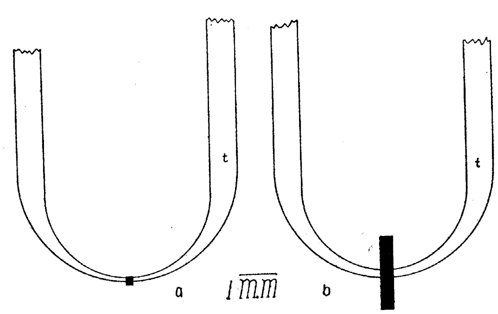

Fig. 15. Sketch of oscillator seal.

frequencies. Thus Figs. 15*a* and 15*b* show halves of two typical oscillator doublets *c*, of which 15*a* is for very short and 15*b* for longer waves. When mounted in the oscillator box, that portion of the doublet of oscillator 15*b*, for instance, which projects from the glass tube *t*, into which it is sealed, is emersed in oil, another part of the length is embedded in glass, and the remainder, which extends into the interior of the tube, is surrounded by air. This gives a complex capacity involving three different dielectric media. In an oscillator of the proportions of 15*b*, the fundamental wave-length divided by the overall length of the doublet λ_0/l has in our experiments run as low as 2.7 for wave $\lambda_0 = 27$ mm, while in such a case as Fig. 15*a*, $\lambda_0 = 2$ mm, a larger proportion of the doublet cylinders are of necessity embedded in glass, hence the capacity is proportionately larger and λ_0/l has in some instances run as high as 4.8. As we go to smaller and smaller oscillators, therefore, this rising ratio makes progress toward shorter and shorter waves increasingly difficult.

Table II. exhibits data concerning oscillator dimensions and measured

TABLE II

Oscillators referred to as "*M*" are oscillators described and used by Möbius. "*La*" refers to Lampa oscillators, and "*Le*" to Lebedew's oscillators; the remainder are oscillators described in the present paper.

Observer or oscillator	λ_0 measured	l, length of oscillator	Diameter	Length of glass seal	λ_0/l
Fig. 8*E*.........	27 mm	10 mm	0.5 mm	1 mm	2.7
Fig. 8*D*.........	21.6	6.6	0.5	0.8	3.3
M.........	16.2	4.5	0.5	2	3.6
La........	8	4	0.5	2	2
Fig. 8*C*.........	11	4	0.5	0.6	2.8
La........	6.1	3	0.5	1.5	2
Fig. 8*B*.........	8.4	2.8	0.5	0.6	3
Le.........	6	2.6	0.5	—	2.3
La........	4	2	0.5	1	2
M.........	7	1.98	0.5	1	3.5
Fig. 8*A*.........	4.2	0.85	0.25	0.4	4.9
Fig. 13*B*.........	1.9	0.4	0.25	0.2	4.8
Fig. 13*C*.........	1.8	0.4	0.25	0.2	4.5

wave-lengths. Column 1 contains the designation of the different oscillators listed, including several oscillators used by other investigators; column 2 gives the corresponding measured wave-lengths reported; column 3, the overall length of the oscillator; column 4, the diameter of the oscillator cylinders; column 5, an estimate of the length of the glass seals; and the last column gives the ratio of column 2 to column 3. If probable values be assigned to the λ_0/l ratio for the Lebedew [2] and Lampa [3] oscillators, it seems very probable that both investigators underestimated the wave-lengths with which they were dealing. Möbius' [4] shortest oscillator of platinum cylinders 1.98 mm long and 0.5 mm in diameter, giving a measured fundamental wave-length of 7 mm, seems to be the smallest oscillator previously used. A ten-year-old rumor concerning 2 mm fundamental waves obtained by Von Baeyer [13] apparently still lacks confirmation.

The chart shown in Fig. 16 displays the present stage of progress

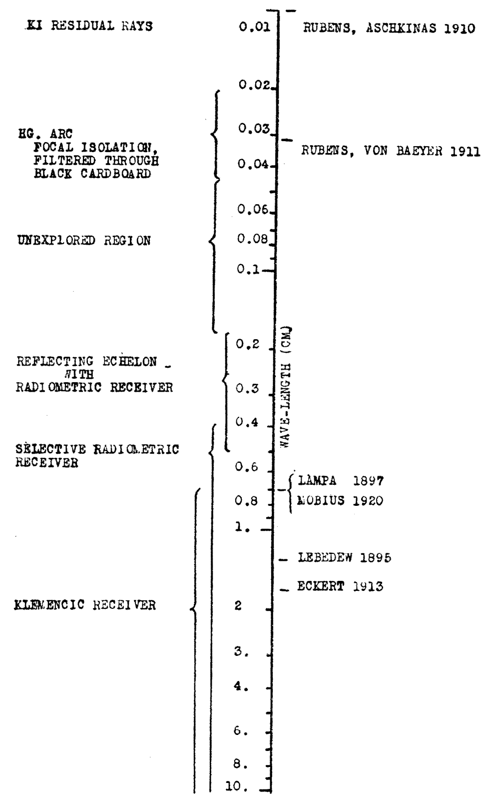

Fig. 16. Spectrum chart.

toward closing the gap still separating the infra-red from the electric wave spectrum. Neglecting wave-length measurements on upper partials which are ripples on a longer fundamental wave, the present experiments have reduced the measured fundamental wave-lengths from 7 mm, reached by Lampa and Möbius, to 1.8 mm, an interval of two octaves. Progress over an interval of two more octaves will connect the electric wave spectrum to Rubens and Von Baeyer's longest heat waves.

The writers are indebted to Miss Ruth Sublett and Miss Marion Smith, assistants in the laboratory, for help in taking observations at the check receiver.

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National Lamp Works,
Cleveland, Ohio

December 13, 1922

[13] H. Rubens, Physik: Kultur der Gegenwart, p. 203, Leipzig, 1915.

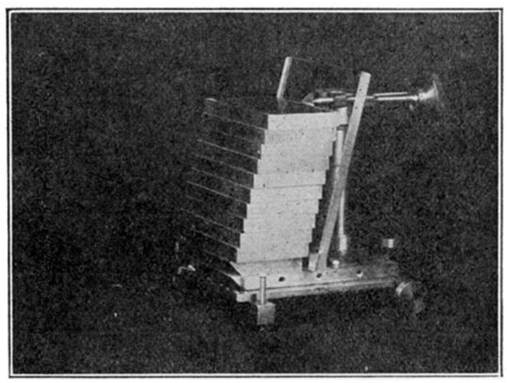

Fig. 10. Photo of echelon.

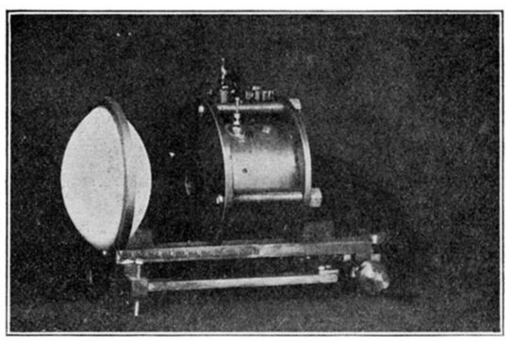

Fig. 2. Photo of oscillator.

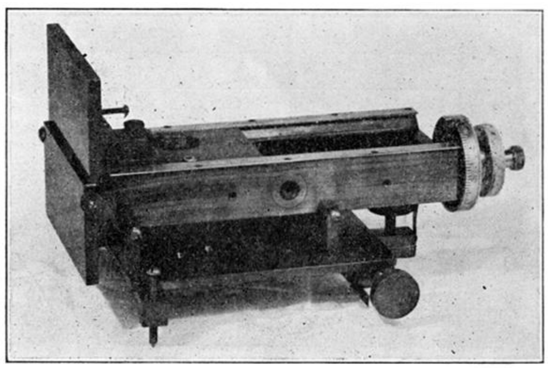

Fig. 5. Photo of Boltzmann interferometer.