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AN ACOUSTIC ANEMOMETER

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of the requirements for the Degree of
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of McGill University.

by

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SECTION I

HISTORICAL.

The first recorded attempt to measure the speed of wind was made by Hooke in 1667. The device he employed was a simple pendulum with a large flat disc at its base. This was suspended so that a portion of the shaft remained above the fulcrum. When the disc was directed towards the wind, it was pushed back, and the part of the shaft above the fulcrum went forward. By attaching a scale alongside this, an indication of the speed of the wind was obtained.

From this first pressure plate anemometer, many types of wind measuring instruments have been developed, utilizing this and other principles, notably Pressure Tube, Cooling Power of Air, and Windmill and Cup anemometers. The pressure plate anemometers are not used now, as they are very erratic in gusty winds, tending to swing backwards and forwards and giving false readings. Added to this is the disadvantage that they must be calibrated as the actual theory of operation is not simple.

Pressure tube anemometers, while very satisfactory under steady conditions, are susceptible to changes in air density and are unsteady in high winds. The most important of this type is the Dines anemometer which is

in use at most weather stations at the present time. This makes use of the fact that wind blown into the mouth of a tube causes an excess of pressure in the tube and wind blown across the mouth causes a suction. The combination of these is an improvement on either used singly and this was first successfully done by Dines. A wind vane is necessary to keep the pressure tube heading into the wind and since the suction in the second tube is sensitive to its orientation, some method of making it insensitive to wind direction had to be found. These two were coupled by Dines together with an excellent manometer, known as the Dines Float Manometer, for measuring the difference in pressure.

Anemometers employing the cooling power of air principle are probably the most accurate. The hot wire type is very accurate for measuring speeds from a few centimeters per second to ten meters per second. The Kata-thermometer anemometer is also fairly accurate in the low speed range. The best of this group is the electrically heated thermometer, which will measure winds between five centimeters per second and thirty meters per second and has the added advantage of being independent of varying temperature and humidity, and nearly unaffected by radiation.

Windmill anemometers consist of rotating vanes, which move about a horizontal axis. Their most important property is the nearly linear relation between the speed of the wind and angular velocity. However they are not much used at the present time due to necessary corrections at low speeds and the problem of directing them into the wind.

The last type of anemometer to be mentioned, the cup anemometer, is probably the most familiar wind measuring device. It originally consisted of several hemispherical cups fixed to a common centre by spokes, and free to rotate in a horizontal plane. Modifications have been introduced, until the Patterson Cup anemometer, which is currently in use consists of three cups, which are conical to give added strength and better performance. The major drawback to this instrument is its moment of inertia, which must be overcome to start its motion, and which continues the motion after the propellant has disappeared. This has been reduced greatly from the first models by the use of aluminium alloys, but the errors in recording gusty winds still remain large, and may, upon occasion exceed ten percent. A cup anemometer has been devised by Mann for measuring high speeds up to two hundred and sixteen miles per hour, but this instrument is unsatisfactory at low speeds.

For a more complete summary of anemometers, reference may be made to "Meteorological Instruments" by Middleton. (1) A paper by Dr. A. Norman Shaw (2) gives comparative data on the performance of several of the above mentioned anemometers.

Up to the present, there does not appear to be available an anemometer capable of measuring wind velocities over a wide range with a fair degree of accuracy which is suitable to general meteorological use. It is the intention of this thesis to indicate how this may be accomplished, making use of a principle entirely removed from those outlined in the preceding paragraphs.

SECTION II

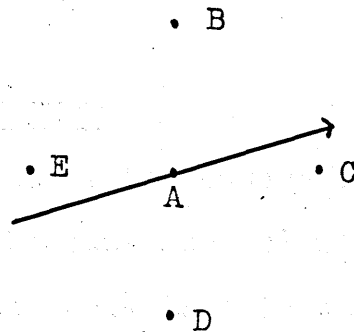
PRINCIPLE OF OPERATION

Fig. 1

The principle of the operation of the acoustic anemometer is as follows: Referring to Fig. 1 above, a sound source is placed at the point A, and receivers at points BCDE, which are equidistant from A. If the receivers are all placed at an equal distance from A, and no wind blows, the time of arrival of the signal from A will be the same at each receiver. Thus if the transmitted signal is of sinusoidal origin, the phase measured at each of the receivers will be identical; and if the emitted sound is in the nature of a pulse of short duration, the time taken to travel from the source A to each receiver will be the same.

The above is true when there is no disturbance due to the wind. If however, a wind were to blow in the direction shown, the phase, or time of arrival of the pulse, at the four receivers would not be the same.

This difference, properly measured and interpreted, will give the velocity, i.e. speed and direction, of the wind.

CONTINUOUS WAVE METHOD

The first attempt to measure the difference of phase (or of time, as the case may be) was done utilizing a continuous wave source. In this case it is the difference in phase that has to be measured and the theory given is simplified to fit the one, instead of the two dimensional case.



Fig. 2

In Fig. 2, S is a sound source emitting a continuous signal, i.e. a signal of sinusoidal form. R_1 and R_2 are two receivers which are spaced equidistant from, and in line with, S . When no wind blows, the phase of the signals received at R_1 and R_2 will be the same. This is equivalent to saying that there is the same number of wave lengths between SR_1 and SR_2 . Suppose that a wind blows in the direction shown. Then the wave lengths in the interval SR_2 will tend to "pile up" or become more

numerous and those between S and R_1 will thin out, or become less numerous. This indicates that the velocity of sound will be increased in going from S to R_1 and decreased in traversing SR_2 by an amount that is equal to the velocity of the wind. The difference can be recorded by recording the difference in phase between the two signals received.

THEORY OF THE CONTINUOUS WAVE METHOD

Suppose the source at S generates in still air a wave whose equation is given by (7)

$$y = A/x \sin \omega (t - x/v), \quad (1)$$

where y is the vertical displacement on a two dimensional plot,

A is the amplitude of the wave at unit distance,

ω is the angular frequency in radians per second,

t is the time in seconds,

x is the distance measured horizontally in centimeters,

v is the velocity of propagation of the wave in centimeters/second.

The term A/x arises from the fact that the energy at a point falls off inversely as the square of the distance from the source, and is proportional to the square of the amplitude. Hence the amplitude decreases

inversely as the distance. Since the variation in amplitude has no effect on the phase angle and is not great enough to prohibit measurements of the phase difference, the quantity A/x will be replaced hereafter by a , the amplitude at distance x from the source.

In the case of the wave travelling to R_1 , (Fig. 2), its velocity will be increased by an amount equal to the velocity of the wind, denoted by v_w , and in the case of the wave travelling to R_2 , its velocity will be decreased by the same amount. Thus if v_s denotes the velocity of sound (i.e. the velocity of propagation of the wave when there is no external disturbances) then the velocity of propagation in SR_1 direction will be $v_s + v_w$ and in SR_2 direction $v_s - v_w$. Hence there are now two equations, derived from equation (1), substituting in the values from $v(SR_1)$ and $v(SR_2)$

$$y = a \sin \omega \left(t - \frac{x}{v_s + v_w} \right); \text{ and } y = a \sin \omega \left(t - \frac{x}{v_s - v_w} \right).$$

From these equations it will be seen that the phase

difference in the two signals at R_1 and R_2 is given by

$$\begin{aligned} & \omega \left(t - \frac{x}{v_s + v_w} \right) - \omega \left(t - \frac{x}{v_s - v_w} \right) \\ &= \frac{\omega x}{v_s - v_w} - \frac{\omega x}{v_s + v_w}, \end{aligned} \quad (2)$$

where now x is the distance from the source to the receivers, which for convenience is the same in both cases, and the other quantities are as previously defined. Thus if $\Delta\phi$ be the difference in phase,

$$\Delta\phi = \omega x \left(\frac{1}{v_s - v_w} - \frac{1}{v_s + v_w} \right) \quad (2a)$$

$$= \frac{4\pi f x v_w}{v_s^2 - v_w^2}, \quad (3)$$

where f is the frequency of the transmitted signal and $2\pi f$ has been substituted for ω .

It may be noted that precise measurements of v_s and v_w may be made by measuring the phase difference between the source and R_1 and also the phase difference between the source and R_2 .

Let the equation for the wave at the source be

$$y = a \sin (\omega t + \alpha). \quad (1a)$$

Then

$$y = a \sin \left(\omega t + \alpha - \frac{\omega x}{v_s - v_w} \right), \quad (1b)$$

and

$$y = a \sin \left(\omega t + \alpha - \frac{\omega x}{v_s + v_w} \right), \quad (1c)$$

will represent the waves at R_2 and R_1 respectively, where α is the phase angle at the source when $t = 0$, and the other quantities are as previously defined.

The phase difference between the signal at the source and the signal at R_2 , $\Delta\psi$, will be given by

$$\Delta\psi = \omega t + \alpha - \omega t - \alpha + \frac{\omega x}{v_s - v_w} = \frac{\omega x}{v_s - v_w} . \quad (1d)$$

The phase difference between the signal at the source and the signal at R_1 , $\Delta\theta$, will be given by

$$\Delta\theta = \omega t + \alpha - \omega t - \alpha + \frac{\omega x}{v_s - v_w} = \frac{\omega x}{v_s + v_w} . \quad (1e)$$

Thus (1d) and (1e) provide two equations for determining v_s and v_w , from which

$$v_s = \frac{\omega x}{2} \left(\frac{1}{\Delta\theta} + \frac{1}{\Delta\psi} \right) ,$$

and

$$v_w = \frac{\omega x}{2} \left(\frac{1}{\Delta\theta} - \frac{1}{\Delta\psi} \right) .$$

In order to simplify the instrumentation, only the phase difference between the signals at R_1 and R_2 was measured, giving (3) above.

It is shown below that v_w^2 may be neglected in comparison with v_s^2 without causing serious error for wind velocities up to 60 m.p.h. This results in simplification of (3) to

$$v_w = \frac{v_s^2 \Delta\theta}{4\pi f x} . \quad (3a)$$

From this equation it is noted that provided the velocity of sound is known, the frequency and distance

of source to receiver are known, and the phase difference measured, then the velocity of the wind may be calculated.

In this method described, the source was a U.S. Army Signal Corps magnetic earphone driven by a Hewlitt-Packard oscillator. The receivers used were crystal earphones manufactured by the Brush Company and the method of measuring phase difference was by means of a cathode ray oscilloscope. The loudness of the transmitted signal was increased by placing over the aperture of the earphone, which was 0.3 mm. in diameter, a piece of glass tubing, in order that the ensemble would behave like a closed organ pipe. This caused a notable improvement in the loudness at a particular frequency, i.e. at resonance for the length of glass tubing employed. Due to the small size of the aperture of the magnetic earphone, the position of the sound source could be accurately determined which is necessary for proper measurements. This however, is not the case with the Brush type crystal earphones, which have a large diaphragm with several apertures leading through the covering material. Consequently their position could not be placed with the same accuracy as the earphone acting as a source. Furthermore, great difficulty was experienced with so

called "wind noise". This disturbance is caused by wind passing over the earphone and setting up eddy currents etc., which affect the diaphragm. These spurious effects of course are transmitted and show up on the measuring device. Wind noise was overcome to some extent, by employing covering membranes similar to those used commercially in outdoor broadcasts, but was not entirely eliminated.

The phase difference was measured by feeding the voltage from the receivers through amplifiers and then on to the horizontal and vertical deflecting plates of the oscilloscope. It is known that when two voltages are thus applied to the oscilloscope, the resulting pattern (Lissajous figure) will be either a straight line, circle or ellipse, depending upon whether the two voltages are in phase, ninety degrees out of phase, or somewhere in between. By observing the figure on the oscilloscope the phase difference may be noted. It is here that wind noise has its effect, causing the figure to distort and blur, and making measurements difficult.

Another difficulty is the question of echoes from nearby objects and the ground itself. The latter may be removed by placing the source and receivers on

stands and directing the source upwards. However objects in the vicinity tend to reflect the sound themselves, and thus cause multiple patterns to appear. A person moving about in the vicinity of the apparatus can cause very disturbing effects. In order to be free from these reflections, it would be necessary to place each of the receivers and the source on a separate stand of such height that a person could move in the neighbourhood without disrupting the results. This would necessitate poles of at least seven feet in length which would have to be rigidly supported so that they would not sway when there was a high wind.

The above problems, together with the fact that the method of measuring was not readily adaptable to the two dimensional case, indicated that a change in sound source, from continuous wave to a pulse would be an improvement.

VELOCITY OF SOUND

Since the measurement of the velocity of the wind is dependent upon the velocity of sound, a derivation of that quantity is given. For this derivation the quantities "condensation" and "compressibility" are required.

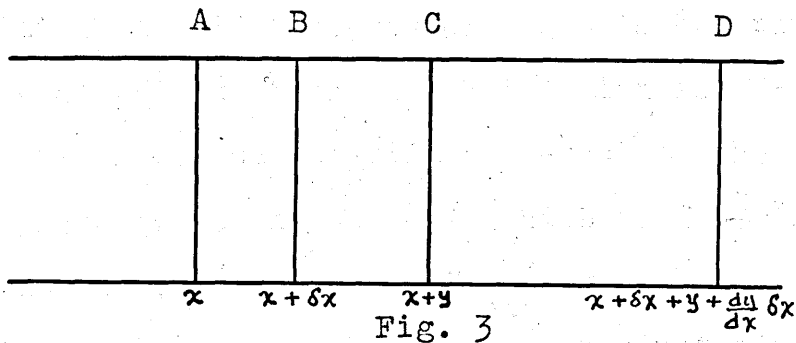
Condensation is the decrease in volume per unit of original volume when a body of gas is compressed. In symbols, the condensation

$$S = - \frac{\delta V}{V} .$$

Compressibility is the fractional decrease of volume produced by unit change of pressure. The elasticity is the reciprocal of the compressibility. Hence if E is the elasticity,

$$E = - \delta p \frac{V}{\delta V} ,$$

where the negative sign indicates that increasing pressure decreases the volume, and where δp is the change in pressure.



Consider a cylinder of gas of unit cross section, illustrated in Fig. 3 along whose length a disturbance is travelling. A and B are two plane sections whose coordinates measured along the cylinder are x and $x + \delta x$.

The initial volume of this slice is δx . At the end of the interval of time δt , the disturbance will have displaced A by an amount y to C, and hence its co-ordinate is now $x + y$. The displacement will not be the same for the other section of the slice, as the displacement will vary with x in the manner $\frac{dy}{dx}$, so that the displacement of section B will be $y + \frac{dy}{dx} \delta x$, and the coordinates of the plane so occupied will be $x + \delta x + y + \frac{dy}{dx} \delta x$. Hence the new volume of the slice will be $\delta x + \frac{dy}{dx} \delta x$ and the increase in volume will be $\frac{dy}{dx} \delta x$. Thus the condensation then = $-\frac{dy}{dx}$, from the above definition. The pressure on a section differs from the normal by an amount which is proportional to its position, and if the pressure on C is δp , that on D is $\delta p + d \frac{(\delta p)}{dx} \delta x$ which on substitution is $ES + E \frac{dS}{dx} \delta x$.

Now the force on the slice is equal to the difference in pressure on the two ends which is $E \frac{dS}{dx} \delta x$, and on substitution, this becomes $E \frac{d^2 y}{dx^2} \delta x$.

This now must be equated to the product of the mass of the slice and its acceleration. Hence

$$E \frac{d^2 y}{dx^2} \delta x = \rho \delta x \frac{d^2 y}{dt^2},$$

where ρ is the density of the gas.

This reduces to

$$\frac{d^2 y}{dx^2} = \frac{\rho}{E} \frac{d^2 y}{dt^2},$$

which is the equation of a plane wave travelling in the x direction with a velocity $\sqrt{\frac{E}{\rho}}$. Thus the velocity of sound is given by $\sqrt{\frac{E}{\rho}}$. It now remains to determine what E, the elasticity, is in this case.

The above derivation for the velocity of sound is based on that given in "Sound" by E.G. Richardson (3).

It was Newton who first established that the velocity of sound is equal to $\sqrt{\frac{E}{\rho}}$. He considered that the air obeyed Boyle's Law, i.e. that the temperature remained constant, giving $p_1V_1 = p_2V_2$, whence he deduced that E was in fact, the absolute pressure. However, when specific values were inserted in the equation $v = \sqrt{\frac{p}{\rho}}$, the resulting velocity was much lower than that actually observed.

The cause of the error was pointed out by Laplace. He suggested that the rise and fall of temperature due to compression and rarefaction did not have time to disappear by conduction. Hence the change is adiabatic and Boyle's Law does not hold. Instead we have the equation,

$$p_1V_1^\gamma = p_2V_2^\gamma,$$

where γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume for the gas.

This expression may be put in the form

$$\begin{aligned} p_1 V_1^\gamma &= p_2 (V_1 - V_1 + V_2)^\gamma \\ &= p_2 V_1^\gamma \left(1 - \frac{V_1 - V_2}{V_1}\right)^\gamma. \end{aligned}$$

Expanding the bracket on the right by the binomial theorem, and neglecting terms containing squares, since $\frac{V_1 - V_2}{V_1}$ will be small,

$$p_1 V_1^\gamma = p_2 V_1^\gamma \left(1 - \gamma \frac{V_1 - V_2}{V_1}\right),$$

or transposing terms

$$p_2 - p_1 = p_2 \gamma \left(\frac{V_1 - V_2}{V_1}\right);$$

but $p_2 - p_1$ is just a force per unit area, or a stress, while $\frac{V_1 - V_2}{V_1}$ is change in volume per unit volume, or strain.

Hence $E = \frac{\text{stress}}{\text{strain}} = p_2 \gamma$. Thus E is dependent upon the ratio of the specific heats as well as the pressure. The value obtained from the equation $\bar{v} = \sqrt{\frac{\gamma p}{\rho}}$ by calculation agrees well with the value obtained experimentally, and thus verifies Laplace's Theory.

The question arises as to how atmospheric conditions affect the velocity of sound, i.e. pressure, temperature and water vapour. From above, the velocity of sound v is given by

$$v = \sqrt{\gamma \frac{p}{\rho}}, \quad (4)$$

where v = velocity of sound in cm./sec.,

γ = ratio of specific heats c_p/c_v ,

p = atmospheric pressure in dynes/cm.²,

ρ = density in grams/cc.,

Now if the air is assumed to obey the perfect gas laws $\frac{p}{\rho}$ may be replaced by $\frac{RT}{M}$ where R is the universal gas constant 0.473 ergs/deg., T is the temperature in degrees Kelvin, and M is the molecular weight. If (8) molecular heats are employed, i.e. specific heats multiplied by the molecular weight, γ may be replaced by C_p/C_v , where C_p and C_v are the molecular specific heats. Also C_p may be replaced by $C_v + R$. Equation (4) may now be written

$$v = \sqrt{\frac{(C_v + R)}{C_v} \frac{RT}{M}}. \quad (5)$$

Thus it is seen that the velocity of sound varies as the square root of the absolute temperature.

There remains to be considered, the variation of the velocity with respect to the remaining quantities, as the moisture content of the air changes. This has been investigated in a thesis by M. Bercovitch and (4) results here show that the error involved in neglecting the effect of moisture content is less than 2% and hence in this experiment is negligible.

THEORY OF PULSED SOURCE

In dealing with a pulsing sound source, it is the time intervals rather than difference in phase that give a means of determining the velocity of the wind. The pulses are emitted at a certain rate, but it is the difference in time taken for any one pulse to reach the receivers that determines the velocity of the wind. To increase the pulse repetition rate is, in effect, to record the velocity of the wind at shorter intervals. The rate is limited, of course, as one pulse must complete its cycle at both receivers before the next pulse arrives at either.

Consider a single pulse of very short duration to be emitted from a source S (Fig. 4), and received at a receiver R .

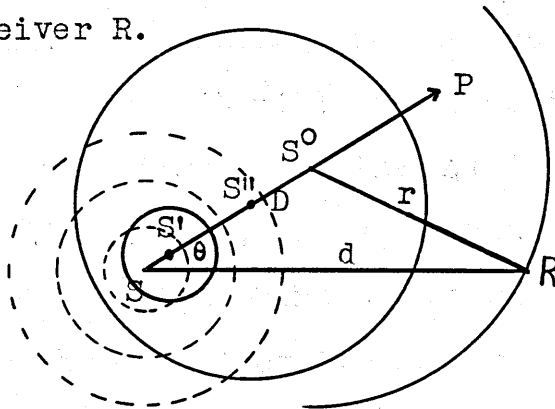


Fig. 4

If there is no wind blowing, the pulse will radiate equally in all directions and becomes the

centre of a ring of sound whose radius is increasing with the velocity of sound. (Dotted circles). This ring will reach R at a definite time given by $\frac{d}{v_s}$ where d is the distance between R and S and v_s is the velocity of sound.

Now suppose that a wind blows with a velocity v_w in a direction making an angle θ with the line joining S and R. Again a single pulse of very short duration is transmitted at S. As before, the sound will travel out in rings from the source, but in this case the source will effectively be moving along SP with a velocity v_w . If the pulse is emitted at $t = 0$, the centre of sound will be at S; but at a time Δt later, the centre of sound will be at a point S'; although the sound itself will be radiating from the centre of sound in concentric rings, it will not be moving out from S in concentric rings. At time Δt later again, the centre will be at S'', and so on, until finally the centre will reach a point S⁰, at which time the ring will reach the receiver R.

Let $S^0R = r$; $SS^0 = D$ and $t =$ time taken for the signal to reach R. Now in this time t , the centre of sound has moved a distance D , and hence

$$v_w = \frac{D}{t}. \quad (6)$$

In this same time t , the signal itself has traversed a distance r with the speed of sound v_s , and thus

$$v_s = \frac{r}{t}. \quad (7)$$

From the geometry of the diagram, it is seen that

$$r^2 = D^2 + d^2 - 2Dd \cos \theta. \quad (8)$$

Substitute in equation (8) for r and D from (6) and (7), and we have

$$(v_s t)^2 = (v_w t)^2 + d^2 - 2v_w t d \cos \theta,$$

or,

$$v_s^2 = v_w^2 + \frac{d^2}{t^2} - 2v_w \frac{d}{t} \cos \theta. \quad (9)$$

Thus if $\theta = 0$, i.e. the wind blows directly along SR then equation (9) reduces to $v_s^2 = v_w^2 + \frac{d^2}{t^2} - 2v_w \frac{d}{t}$

$$= (v_w + \frac{d}{t})^2.$$

Whence $d = (v_s + v_w)t$ which is what one would predict.

It is interesting to note however, that if $\theta = \pi/2$ or the wind blows at right angles to SR, the equation (9) reduces to

$$v_s^2 = v_w^2 + \frac{d^2}{t^2},$$

which shows that if the wind were to have a high speed in a direction at right angles to SR, it would appreciably affect the time of arrival of the pulse at R, although the effect is generally negligible.

signal will be received at R_1 , and the centre will have moved a distance d_1 along SP to M. At time t_2 after the signal has been transmitted, it will reach R_2 , and the centre will have travelled a distance d_2 along SP to a point N. Let $MR_1 = r_1$ and $NR_2 = r_2$. Then as before,

$$r_1^2 = d_1^2 + D^2 - 2d_1 D \cos \theta,$$

and

$$r_2^2 = d_2^2 + D^2 + 2d_2 D \cos \theta, \quad (10)$$

where

$$r_1 = v_s t, \quad r_2 = v_s t_2, \quad d_1 = v_w t, \quad d_2 = v_w t_2.$$

Substituting these in equation (10), we have

$$(v_s t_1)^2 = (v_w t_1)^2 + D^2 - 2v_w t_1 D \cos \theta,$$

$$(v_s t_2)^2 = (v_w t_2)^2 + D^2 + 2v_w t_2 D \cos \theta.$$

Subtracting,

$$(v_s^2 - v_w^2) (t_2^2 - t_1^2) = 2v_w (t_2 + t_1) D \cos \theta,$$

or

$$t_2 - t_1 = \Delta t = \frac{2v_w D \cos \theta}{v_s^2 - v_w^2}. \quad (11)$$

Thus when D , v_s , and θ are known and Δt is measured, the velocity of the wind may be calculated.

It is well to note here the orders of magnitude of v_s^2 and v_w^2 . At 0°C the velocity of sound is 331.2 m/s. A wind of 60 m.p.h. corresponds to a v_w of 26.8 m/s.

In the one dimensional acoustic anemometer, there are two receivers, spaced equidistant from, and in line with, the source S . The time of arrival of the signal at these receivers will not be the same unless the velocity of the wind is zero or the direction of the wind makes an angle of ninety degrees with the line joining them (which, from above, passes through the source S .)

Let the two receivers be R_1 and R_2 and consider a wind to blow with a speed v_w making an angle θ with the line $R_1 R_2$. (Fig. 5). Suppose the velocity of sound to be v_s and the distance of the receivers from the source to be D .

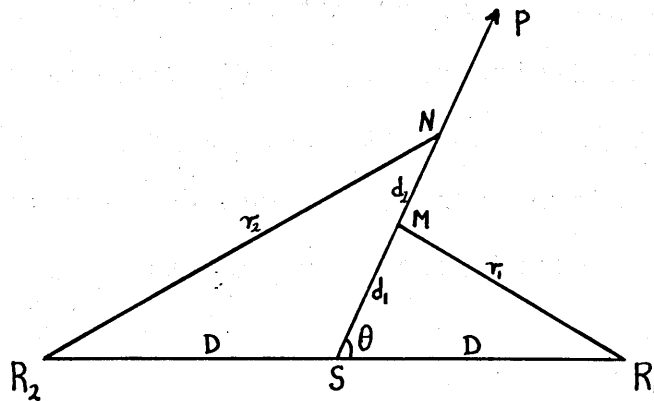


Fig. 5

Then from the previous discussion, when a pulse is emitted from S , the centre of the signal will travel along SP with a velocity v_w . After a time t_1 , the

Thus v_s^2 is of the order of 1040×10^2 m/s and v_w^2 is of the order of 8.4×10^2 m/s. Hence if v_w^2 were neglected in the denominator of (11), the error would not be 1% for a velocity of wind of 60 m.p.h. Doing this and rewriting (11), we have

$$v_w = \frac{v_s^2}{2D \cos \theta} \Delta t, \quad (12)$$

which formula is sufficiently accurate for most measurements.

In contrast to the continuous wave source, this method is readily adaptable to two dimensions, since it is times that are compared and not phases. In addition to this, the effects of wind noise may be discriminated against and thus cause no ill effects in the measurements. From the mechanical point of view, the pulse may be generated very simply and with a compact circuit, as opposed to the continuous wave signal which required an audio oscillator.

SECTION III

CIRCUITSDescription.

As has been stated, the source of sound is a sharp-fronted pulse. This pulse is obtained by means of a relaxation oscillator circuit, used in conjunction with the small magnetic earphone. (See Diagram 1). The condenser is large so that the pulse emitted by the earphone will be loud. The charging resistor is chosen so that the condenser voltage will rise nearly to the maximum in 1/10 sec.

The frequency of oscillation (5), is given approximately by

$$f = \frac{1}{RC \log_e \frac{E_B + E_S - E_T}{E_B - E_S}}, \quad (13)$$

where f is the frequency of oscillation,

R is the charging resistor in megohms,

C is the capacitance in μ farads,

E_B is the supply voltage,

E_S is the striking voltage,

E_T is the tube drop.

Insertion of the given circuit values in this equation gives a frequency of oscillation of approximately 10 per second.

The receivers consist of crystal earphones each feeding into a three stage amplifier with R/C coupling. (See Diagram 2). These amplifiers are of standard design with the capacitance values chosen to give best performance in the high frequency range, since the sharp front of the pulse consists of high frequencies.

The device employed to measure the time differences is a cathode ray tube used in conjunction with two switching circuits. (See Diagram 3). Each of these switching circuits is associated with one of the above mentioned amplifiers. Their purpose is twofold; first to act as an "on" switch and hence permit the beam of the cathode ray tube to be deflected, (and to determine the deflection) and secondly to stop the deflection and allow the beam to recentre itself, and thus permit the procedure to be repeated.

In Diagram 3, the thyatron is normally not conducting. However when a positive pulse is applied to the grid from the amplifier, the tube conducts, and the condenser C_c starts to charge. Due to the presence of the pentode in the plate circuit of the thyatron, the charging of the condenser is linear. This change in voltage is transmitted to the grid of a triode amplifier, from which it passes on amplified to one horizontal plate

of the cathode ray tube, thus causing the beam to deflect from centre. The identical procedure happens to the pulse from the other amplifier, and the voltage in this case is applied to the second horizontal deflecting plate. Hence if the pulse emitted by the source arrives at the receivers at the same time, there would be no deflection of the beam on the cathode ray tube screen, since both horizontal plates would be charged to the same potential at the same time. If, however, pulse A arrives first, the deflection plate corresponding to this receiver will start to charge while the other will not, and the spot will move across the screen. When the pulse arrives at B, its deflection plate will charge, and the spot will stop moving across the screen and remain stationary at some point other than the centre, the distance from the centre depending upon the length of time the deflection plate corresponding to receiver A was charging before B started.

This is seen more clearly with the aid of Fig. (a). For the moment only the condensers in the cathodes of the thyratrons will be considered, as they control the action and the triodes act simply as amplifiers.

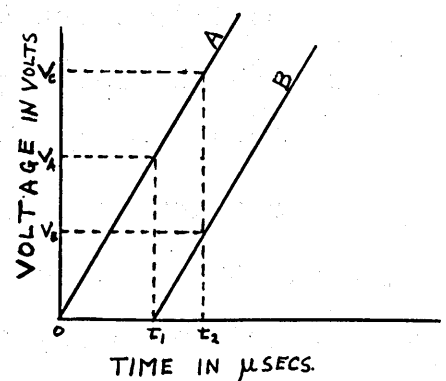


Fig. (a)

At time zero, the pulse reaches amplifier A, which causes thyatron A to fire and condenser C_{cA} to charge linearly. This is represented by line A in the diagram, the slope of the line being a function of the charging current and the condenser value.

At time t_1 μ seconds later, the pulse reaches microphone B, which transmits it through amplifier B to the grid of thyatron B, causing it to strike and hence the condenser C_{cB} to charge. Since the circuit elements are the same in both A and B, the charging curve of C_{cB} will be parallel to A and since the charging is linear, both will be straight lines. Hence at time t_1 there will be a voltage of V_A volts on C_{cA} and a voltage of zero on C_{cB} . At a time Δt μ seconds later at t_2 , the voltage on C_{cA} will be V_C and that on C_{cB} will be V_B . Since A and B are straight lines, $V_C - V_B = V_A$ and the difference of the voltage on the condensers will be constant. Now these voltages are amplified and passed on to the deflection plates of the cathode ray tube and hence there is a constant difference of voltage on the plates. This causes the spot to remain stationary after a time t_1 . How far from centre the spot stops depends upon the length of time t_1 (from Fig. (a)), and

this in turn depends upon the time elapsed from receipt of the signal at receiver A to the receipt of the signal at receiver B. It has been shown previously that if the receivers are equally spaced from the source, this time difference is proportional to the velocity of the wind. If the pulse were to arrive at receiver B first, the analysis would be the same except the beam of the cathode ray tube would be deflected in the opposite direction.

Since the pulses are emitted at the rate of ten per second from the source, this procedure must be repeated ten times a second, and hence the thyratrons must be cut off soon after the spot reaches its stationary position. This is accomplished by making the pentode non-conducting. (See below.)

The length of time the condensers charge is of the order of tens of μ seconds, and the path of the deflecting beam would be difficult to see, although the final position would be discernible. In order to facilitate measurements, a line is desirable, and since this is unobtainable while the beam is deflecting, it must be accomplished while the beam is returning to centre. To do this, the voltages must be removed from the condensers slowly and this is the purpose of the large resistors in the cathode circuits of the thyratrons.

When the pentode is quenched, the charging current ceases, and the condenser C_c discharges through the resistor R_c (Diagram 3). If the time constant, i.e. $R.C.$, of this circuit is large, the voltage on the condenser will fall gradually, and hence the deflected beam will recentre itself slowly, giving a visible line.

Figs. (b) (1) and (b) (2) give plots of condenser voltages against time and to the same scale, resultant condenser voltage against time. The resultant condenser voltage is the excess of voltage on one condenser over the voltage on the other.

The scales are the same in both cases, and the time scale is greatly contracted after t_2 in order to present the picture.

In Fig. (b) (1), lines A and B denote the rise and decay of the voltages on condenser A and B. The plot starts at $t = 0$ when thyatron A strikes. At time t_1 thyatron B strikes and at t_2 , both chargings are arrested by the quenching circuit. When the supply voltage

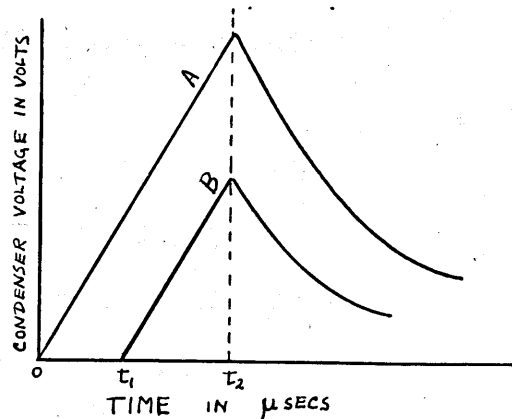


Fig. (b) (1)

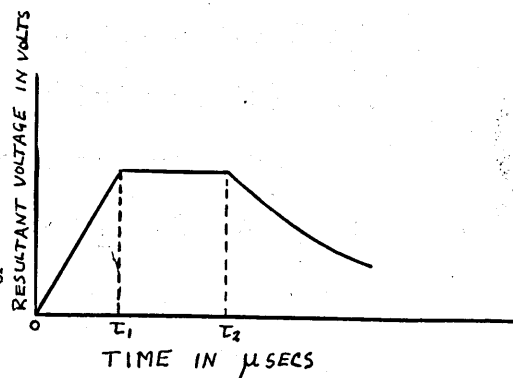


Fig. (b) (2)

is cut off from thyatron A, the voltage on the condenser C_{cA} will decay according to the equation

$$E_1' = E_{1M} e^{-t/RC}, \quad (14)$$

where E' is the voltage at any time t on C_{cA} ,

E_M is the maximum voltage attained on the condenser C_{cA} ,

e is the base of natural logarithms,

R is the resistance through which the current discharges in megohms,

C is the condenser value in pfarads.

At the same time, the supply is cut off from thyatron B, and the voltage C_{cB} will decay according to the equation

$$E_2' = E_{2M} e^{-t/RC}, \quad (15)$$

where E_2' is the voltage at any time t on C_{cB} ,

E_{2M} is the maximum voltage attained on the condenser C_{cA} and R and C are as defined above. The individual curves are shown in Fig; (b) (1).

It is the resultant voltage that controls the deflection on the cathode ray tube, and the curve for resultant voltage versus time is shown in Fig. (b) (2). From time $t = 0$ to $t = t_1$, the voltage is just the voltage rise on condenser C_{cA} . At $t = t_1$, the voltage

begins to rise on C_{CB} and thus, as previously noted, the resultant voltage remains constant. Both chargings stop at $t = t_2$, and the resultant voltage decreases in an exponential manner, given by, making use of equations (14) and (15) above

$$E_1 - E_2 = \Delta E = (E_{1M} - E_{2M}) e^{-t/RC}, \quad (16)$$

where ΔE is the resultant voltage at any time t .

Thus the decay of the resultant voltage will also be an exponential whose time constant is identical with the time constants of equations (14) and (15). The circuit values are chosen so that this resultant voltage will be nearly zero when $t = 0.1$ second, and hence the procedure may be repeated at the rate of ten times a second.

The quenching circuit for the pentodes is given in Diagrams 3 and 4. A third microphone is employed as the trigger for this circuit. It is situated further from the source than either receiver, the increase in distance being determined by the longest time required by the pulse to reach either microphone. The increase must be just greater than the distance covered by the pulse in this time, so as not to quench the circuits until both thyratrons have fired.

This third microphone also feeds into a three stage resistance capacitance coupled amplifier, of slightly different but still standard design (Diagram 2a). The output of this amplifier is used to trigger a self-biased thyatron (Diagram 5) from which a constant voltage pulse is fed onto the grid of a triode. From the plate of this triode the pulse, amplified and shifted 180° in phase so that it is now negative, is coupled by two condensers to the control grids of the pentodes in the switching circuits. This negative voltage on the grids causes the pentodes to become non-conducting, and hence the thyatrons quench.

The entire circuit diagram is given in block form in Diagram 7.

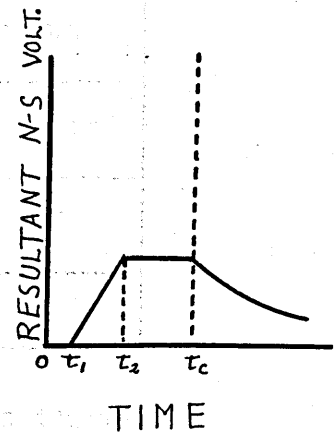
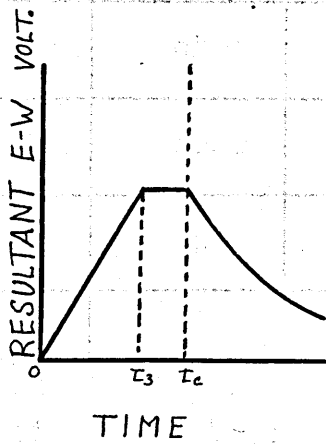
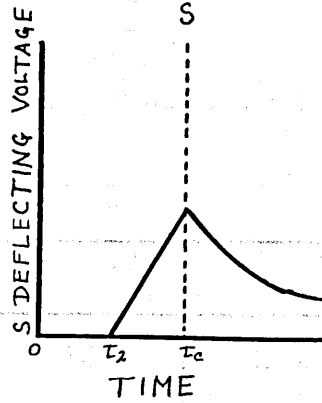
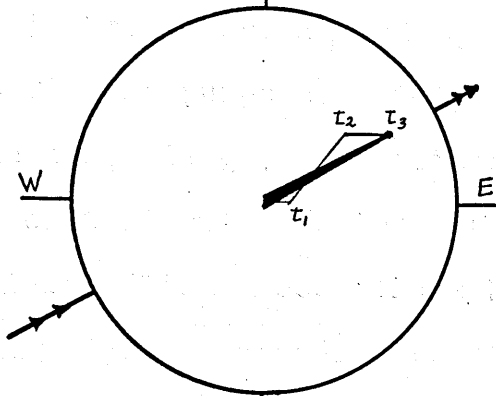
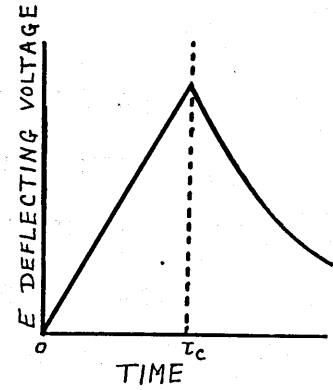
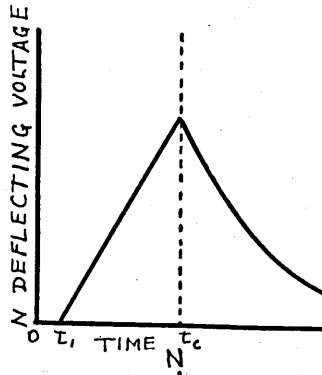
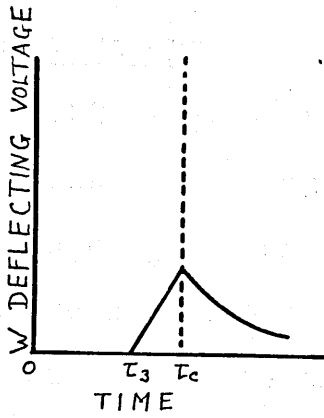
A diagrammatic representation of the principle of operation of the cathode ray tube as a means of displaying the velocity of the wind is given below. Although this thesis reports only the operation in the one dimensional case, the diagram shows how it may be extended to meet the two dimensional problem. Two receivers complete with amplifiers and switching circuits must be added. The four receivers are placed equidistant from the source in the North, South, East and West directions and the voltages they control are

applied to the four deflecting plates of the cathode ray tube. In order to demonstrate how these separate voltages govern the movement of the beam, four diagrams are included giving the deflecting voltage corresponding to each of the receivers. Each of these four diagrams is plotted to the same scale.

Consider the wind to blow in the direction indicated. Then by the theory given, the pulse will reach the East receiver first. At the time taken as $t = 0$, a deflecting voltage will start to rise on the East deflecting plate, causing the spot to travel across the tube in that direction. At time t_1 , the North receiver will pick up the pulse and thus a voltage will start to rise on the North deflecting plate. This voltage combined with the voltage on the East deflecting plate, will cause the beam to proceed in the manner shown between t_1 and t_2 . At time t_2 , the pulse will be picked up by the South receiver and the beam will follow the course shown by t_2 and t_3 . Finally at t_3 the West receiver will be actuated and the beam will come to rest, remaining at that point until all thyratrons are quenched at t_c . At time t_c the spot will move to recentre itself following the bold line, moving quickly at first and slower as it approaches the centre, according to the

decay of the voltages on the condensers in the cathode of the thyratrons.

Since the motion to t_3 takes place in 500 μ seconds, the out-going path will not be discernible, but the recentering path, taking of the order of 0.1 seconds would be visible. This procedure repeated ten times a second gives a line practically straight, whose length is proportional to the speed of the wind and whose direction gives the direction of the wind.



CIRCUIT VALUES

Table I gives the values for the circuit generating the pulse. (Diagram 1.) The values E_B and E_t are fixed and C and E_s chosen to fit the purpose. It is advantageous to have the capacitance large, and striking voltage high so as to make the emitted pulse as loud and of as short duration as possible. With these values known, the charging resistance is given according to the equation (13) for the approximate frequency of oscillation. R_b is large so that a fine adjustment of the frequency is possible and R_g and R_p are protective resistances.

TABLE I

R_c	ohms	42000	2 watt
R_p	ohms	100	2 watt
R_g	ohms	30000	1/2 watt
R_b	ohms	50000	wire wound
C	$\mu f.$	1	3000 V
L	earphone		

The circuit values are standard for the three amplifiers (6). The amplifier for the cut-off micro-

phone has decoupling in two stages in order to insure against oscillations.

Table II contains the values used in the circuit diagram 3. It is decided that the maximum voltage to which C_c is allowed to charge is 20 volts. Since the charging is linear

$$Q = IT = CV, \quad (17)$$

where Q is the charge in coulombs,

I is the current in amperes,

T is the time in seconds,

C is the condenser value in farads,

V is the voltage on the condenser in volts.

In order to determine the size of condenser necessary, the duration of charging must be known. From the general theory there is the equation

$$\Delta t = \frac{2v_w D}{v_s^2}, \quad (18)$$

(Equation 12 with $\theta = 0$).

where Δt is the time difference between the arrival

of the pulse at receiver A and B,

v_s is the velocity of sound,

v_w is the velocity of the wind,

D is the distance of the receivers from the source.

The distance D is one meter. The velocity of

sound is known, 331.2 m/s at zero degrees C. The instrument is designed to record wind velocities up to 60 m.p.h. which is 26.8 m/s. Insertion of these values in equation (15) gives $\Delta t = 488 \mu\text{secs}$. Hence the value of T in equation (17) should be 500×10^{-6} seconds to allow for a slight margin.

The charging current is fixed at 2 milliamperes and inserting these values in equation (17) gives C_c equal to 0.05 μf . When the value of C_c has been determined the cathode resistor may be calculated from the relation

$$\Delta E = E_0 e^{-t/RC}, \quad (16)$$

The value of E_0 is 20 volts, C is 0.05 μf , and ΔE should fall to 1/50 volts in less than 0.1 seconds. Insertion of these values in the equation gives R_c equal to 0.2 megohms.

The values of the resistors in the grid circuit of the thyatron are chosen to reduce the voltage pulse on the grid from the amplifier to the minimum necessary to strike the tube. R_Y is large so that the grid of the pentode will go negative with respect to the cathode when the negative voltage pulse arrives through C_g . R_P is a stabilizing resistor and is large so as to have little effect when the thyatron strikes.

TABLE II

R_Y	M ohms	1
R_P	M ohms	4.5
R_C	M ohms	0.2
R_b	M ohms	0.5
R_g	M ohms	0.1
R_d	ohms	47000
C_g	$\mu f.$	0.001
C_c	$\mu f.$	0.05

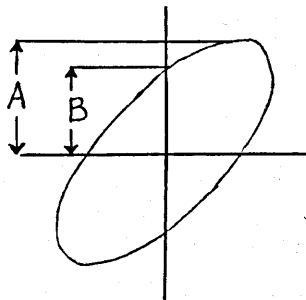
The circuit values for the triode in the cut-off circuit and for the triodes feeding to the cathode ray tube are chosen so that the amplification is distortionless.

SECTION IV

RESULTSA. Continuous Wave Method.

The continuous wave method was abandoned in favour of the pulsed source to simplify the design and to avoid errors due to reflection and amplitude change. It was by a continuous wave method, however, that sound waves have actually been used to measure wind speed.

Sinusoidal voltages from two receivers were injected onto the horizontal and vertical deflecting plates of an oscilloscope and Lissajous figures were obtained. The pattern was observed to vary as the velocity of the wind varied. The phase difference between the two deflecting voltages was determined from the relation $\sin \alpha = \pm \frac{B}{A}$ where α was the phase difference and B and A were as indicated in the figure. The confusion as to sign arises from the fact that $\sin \alpha$ and $\sin (180 - \alpha)$ have the same absolute value, but differ in sign.



Attempts were made to record the intercept B at short intervals, and hence calculate α provided the

amplitudes of the waves remained constant. There were two short-comings attached to this procedure. The first is that the amplitude did not remain constant, largely due to wind noise, as has been previously mentioned. The second and more serious effect was that a hand or small object moved in the vicinity of either receiver caused a shift in phase. This latter trouble was caused by reflections. The combination of these spurious effects made readings difficult to obtain and often those that were obtained were subject to large errors.

This method, tried experimentally, did show that the experiment was proceeding in the right direction and that variations in the velocity of sound due to the velocity of the wind could be used as the basis for a wind measuring device.

B. Pulsed Source.

Using a pulsed source, laboratory tests to determine the velocity of sound in the one dimensional case have been made. It is recalled that in the theory of operation of the anemometer the two receivers are placed at an equal distance from the source and that a wind blowing along the line of receivers and

source creates a time difference in arrival of the pulse at the two receivers. It is this time difference that is recorded. In order to create a time difference in the laboratory the receivers were placed at unequal distances from the source. This has the same overall effect as a wind blowing.

The photographs shown below indicate how the length of the line on the cathode ray tube varies as the inequality of the distances of the receivers from the source is varied. When the receivers are equidistant from the source there is a spot only. As one receiver is moved closer, and the other further from the source the line lengthens. Depending upon which receiver is closer, the line moves to the right or left and its length is proportional to the difference in the time of arrival of the pulse at the two receivers.

In order to place the receivers at the correct distance to simulate a given wind it is necessary to know the time difference created by the wind when the receivers are placed one meter from the source.

Table III below gives the time differences corresponding to various velocities of the wind.

TABLE III

Velocity of wind	t
m.p.h.	μsec
60	488
30	244
20	163
15	122
10	82

Using these results, Table IV gives the distances the microphones must be changed from 100 cm. in order to obtain a reading equivalent to the velocity of the given wind. (One receiver must be moved toward the source and the other away from the source.)

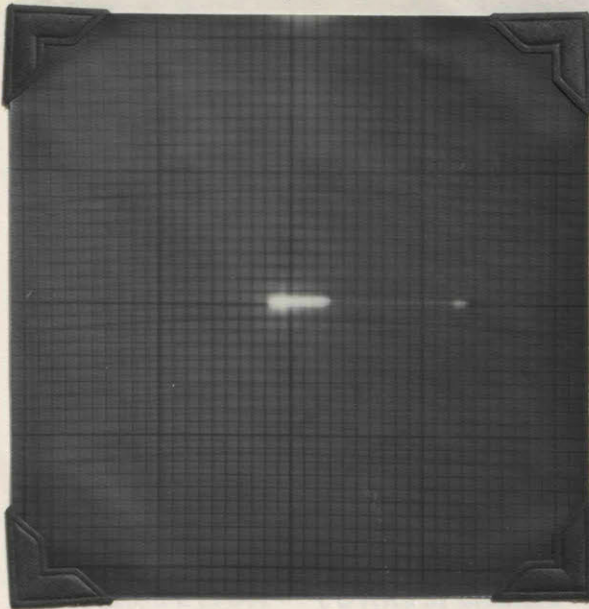
TABLE IV

Velocity of wind	distance
m.p.h.	cms
60	8.08
30	4.04
20	2.69
15	2.02
10	1.35
0	0

In this manner the photographs indicating the velocity of the wind were obtained.

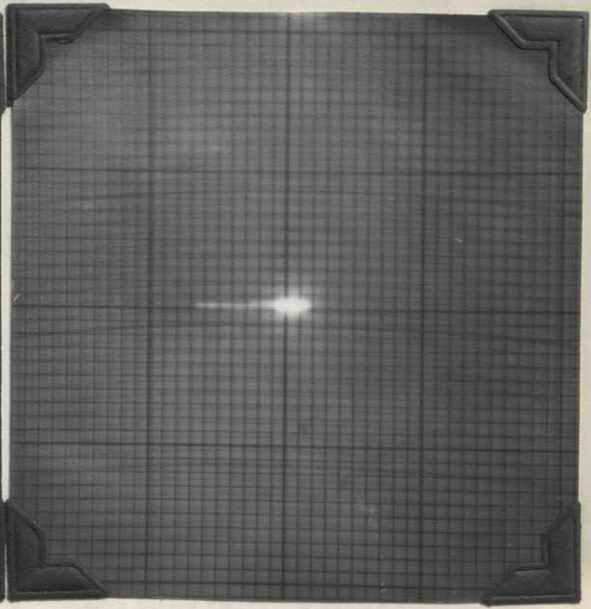
The laboratory tests carried out with the pulsed source have indicated that the theory is correct. Certain discrepancies have occurred in the measurements, which may be attributed to circuit elements. In order to obtain zero reading, the two microphones were not spaced equidistant from the source. This results from the fact that the circuits associated with the microphones may not be identical. In order to make accurate measurements, all circuit values used in one switching circuit must be identical with those inserted in the other. If this is not the case, there is enough coupling between component parts of a switching circuit to cause it to behave quite differently from its counterpart. The actual error in the spacing of the microphones was found to be 10 cms when one was 100 cms from the source. The distances the microphones were moved in order to simulate a wind agreed to within 5% of those obtained by calculation.

1



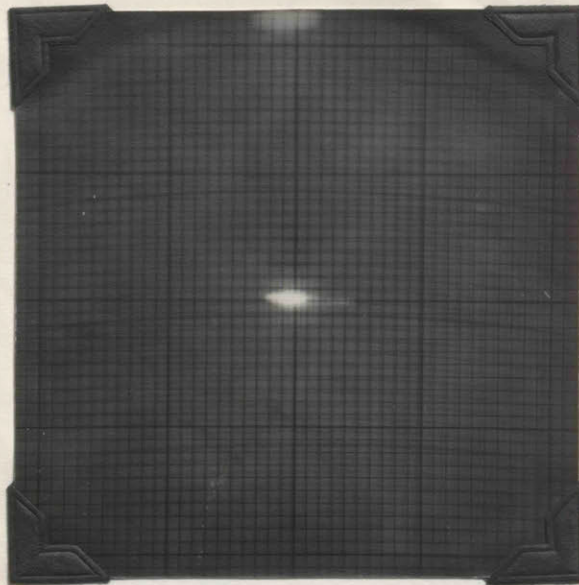
DEFLECTION CORRESPONDING
TO A WIND OF 60 M.P.H.

2



DEFLECTION CORRESPONDING
TO A WIND OF 30 M.P.H.

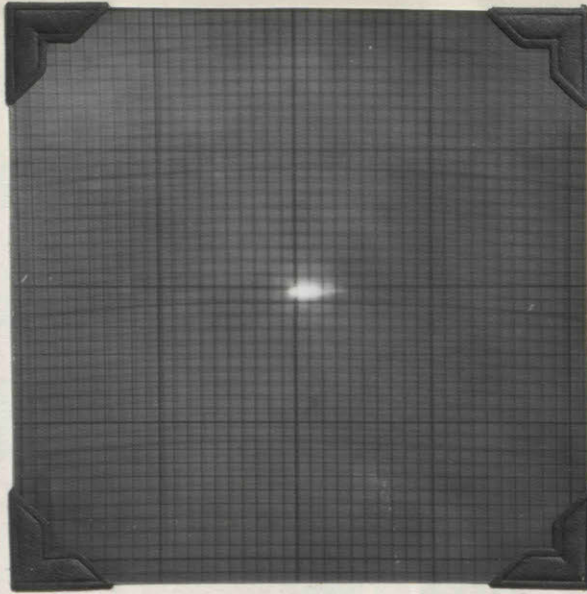
3



DEFLECTION CORRESPONDING
TO A WIND OF 20 M.P.H.

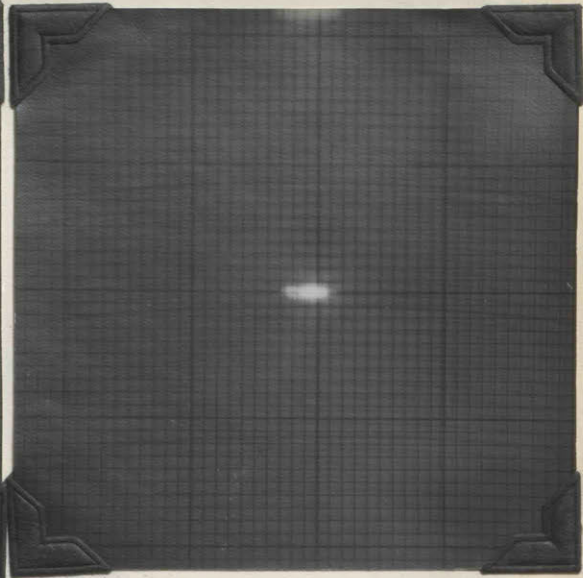
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4



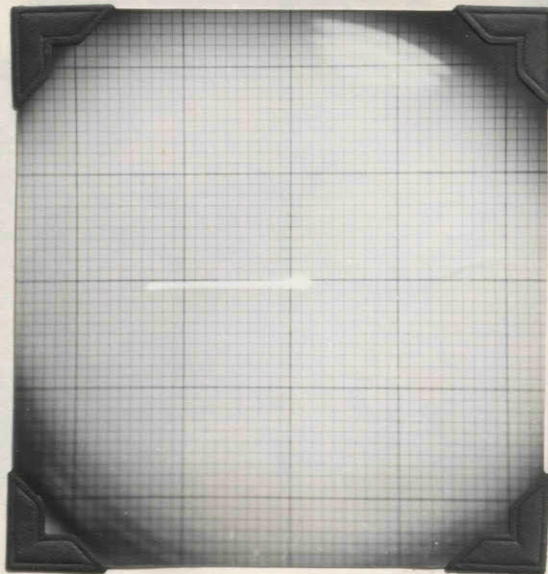
DEFLECTION CORRESPONDING
TO A WIND OF 15 M.P.H.

5



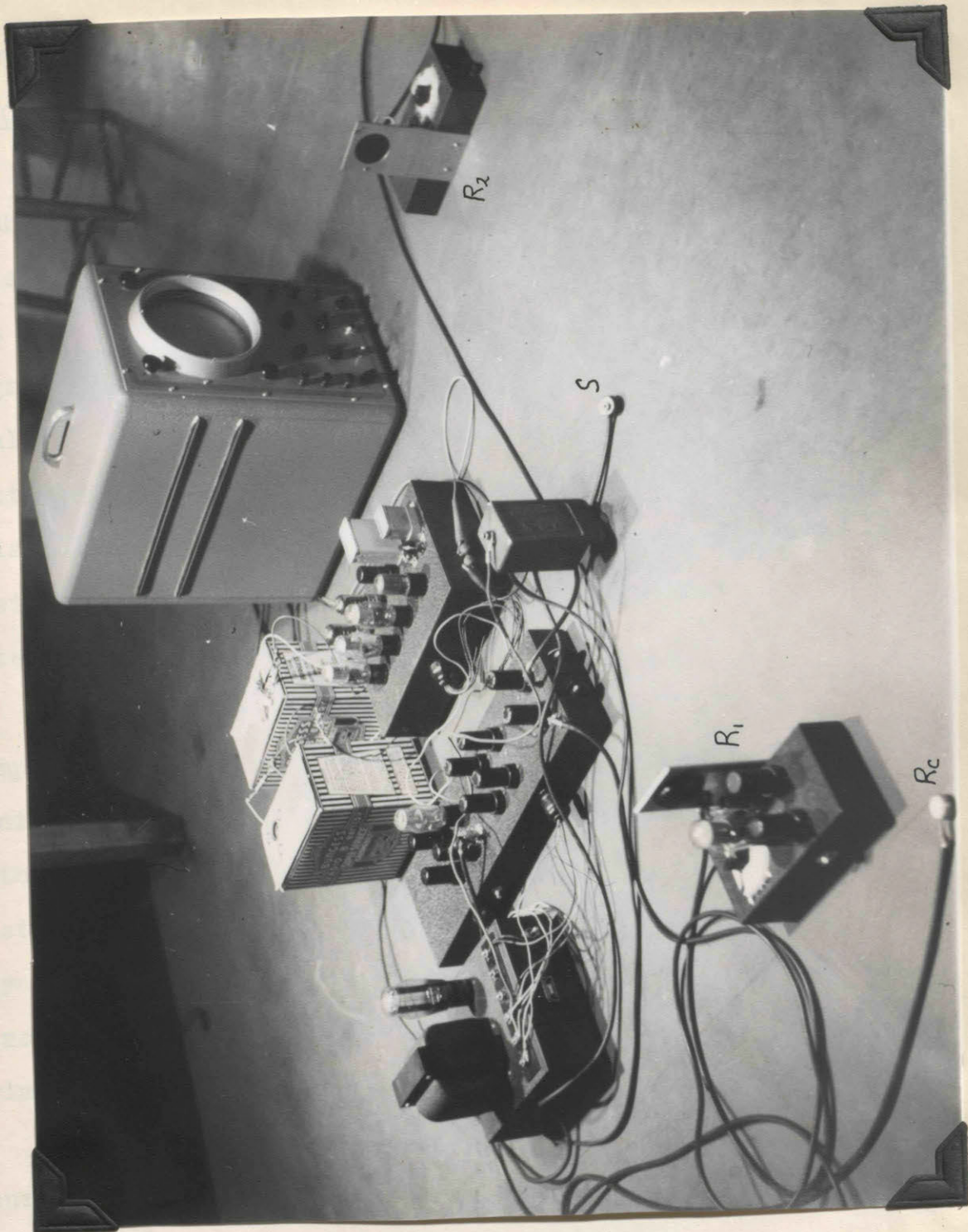
DEFLECTION CORRESPONDING
TO A WIND OF 10 M.P.H.

6



DEFLECTION CORRESPONDING
TO A WIND OF 40 M.P.H.

THE SCREEN OF THE C.R.O. WAS PHOTOGRAPHED FROM A GREATER DISTANCE IN THIS CASE WHEREAS THE ACTUAL TRACE WAS NOT. COMPARISON OF THIS TRACE WITH THAT IN PHOTOGRAPH I WILL RESULT IN THE CORRECT INTERPRETATION.



PHOTOGRAPH OF APPARATUS
 R_1, R_2 - RECEIVERS R_c - CUT-OFF RECEIVER
 S - SOURCE

SECTION V

CONCLUSIONS

In making measurements of the velocity of wind with the continuous wave method, the variation of amplitude and reflections were great handicaps, as was pointed out in the results. To overcome this, the sinusoidal signals were applied to the deflecting plates through small condensers. These condensers caused the sinusoidal voltages to become, in effect, a series of pulses. The pulses appeared on the cathode ray tube display, and their orientation to one another provided a means of determining the velocity of the wind.

At this point it was realized that in order to simplify circuits and reduce the number necessary to a minimum, a pulsed source would be an improvement. Although the continuous wave method was not carried past this point, there does not appear to be any reason why it could not be developed. Great simplification of circuits is possible with a pulsed source, and it was primarily for this reason that the method was adopted.

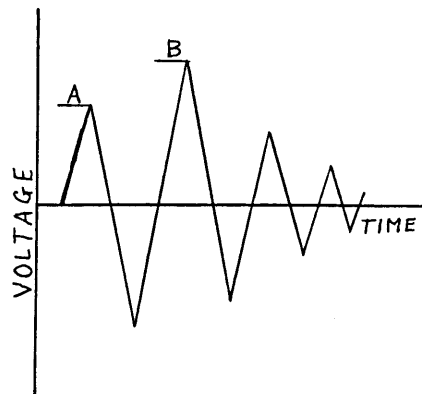
The results of laboratory tests with the pulsed source verify that this method is suitable for use as an anemometer.

Further changes in the circuit are indicated, however, to reduce to a minimum the number of tubes necessary and to improve the accuracy. Since the full gain of the

three amplifiers is not used, it seems probable that a two stage R/C coupled amplifier would be sufficient for the purpose in all three cases.

The limitations to attaining greater accuracy with the present circuit are twofold. The first occurs in the switching circuits as has been pointed out, and the second in reading the display on the cathode ray tube.

The thyatron in the switching circuit is fired by a pulse from an amplifier which in turn is triggered by one of the receivers. In spite of the fact that the pulse generated is a saw tooth, the signal received by the amplifier is of the form shown in the adjacent figure. This distortion of the pulse is caused by the receiver, which is incapable of reproducing faithfully the signal it receives.



Since it is this distorted pulse that triggers the thyratrons in the switching circuits, it is necessary that they should both be fired by either peak A or peak B. The large error in placement of the receivers mentioned in the results could be caused partially by one

circuit triggering on peak A and the second on peak B. Provided the receivers behaved identically, this could be overcome by fine adjustment resistors in the grid circuits. It is not feasible to increase the amplification much greater than that necessary to strike the tube, as when the voltage is too large, a grid current will flow.

From the photographs shown, it is noted that under present operating conditions, a simulated wind of 60 m.p.h. causes a deflection of approximately 15 divisions. It is doubtful if accurate readings could be recorded by attempting to read the display to better than half a division. Since the scale is linear, the accuracy for winds up to 60 m.p.h. is limited to approximately 2%. The distance the spot will move from centre for a given deflecting voltage is a function of the type of cathode ray tube employed, and may be predicted from a knowledge of the deflection sensitivity. By increasing the deflection to 30 divisions to correspond to a wind of 60 m.p.h. the reading accuracy may be increased to nearly 1%. This could be accomplished by increasing the amplification of the condenser voltages in the cathode circuits of the thyratrons, (which would involve an increase in the number of components necessary) and possibly a more suitable choice of cathode ray tube.

The present instrument has been built up with the object of measuring winds up to 60 m.p.h. If, however, it is only necessary to record winds up to 30 m.p.h., all that is required is a change of condensers, (C_c), in the cathodes of the thyratrons in the switching circuits. It is recalled, that to determine the value of C_c , (page 39), use was made of equations (17) and (18), with the velocity of wind given as 60 m.p.h. or 26.8 m/sec. A velocity of 30 m.p.h. (13.4 m/s) inserted in equation (18) gives $\Delta t = 244$ μ secs, and hence the value of T in equation (17) is now 250 μ secs. This gives a value of 0.025 μ f for the condenser C_c . In this manner a deflection of 14 divisions may be obtained to correspond to a velocity of wind of 30 m.p.h. The recording accuracy is hereby increased to approximately 1%.

In a similar manner, the instrument may be constructed to record winds only up to 15 m.p.h. The three ranges (and more if required) may be built into the instrument by means of switches.

The anemometer described in this thesis was not designed to compete with commercial instruments, but rather to investigate the possibilities of utilizing variations in the velocity of sound caused by wind as a basis for determining the velocity of wind. The results of the

laboratory tests indicate that an instrument designed on this basis is satisfactory, although an increase in component parts is necessary before greater accuracy is obtainable.

LEGEND FOR DIAGRAM 1

R_c	ohms	42000	2 watt
R_p	ohms	100	2 watt
R_b	ohms	50,000	wire wound
R_g	ohms	30,000	1/2 watt
C	pf.	1	3000 V
E_B	volts	300	
E_b	volts	4 1/2	
L	earphone		

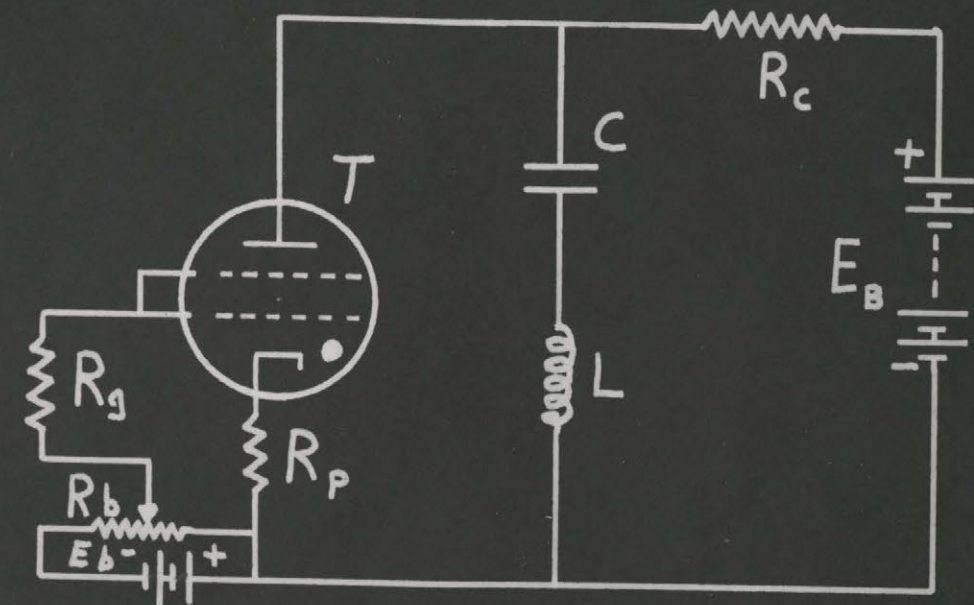
T - 2050

LEGEND FOR DIAGRAM 6

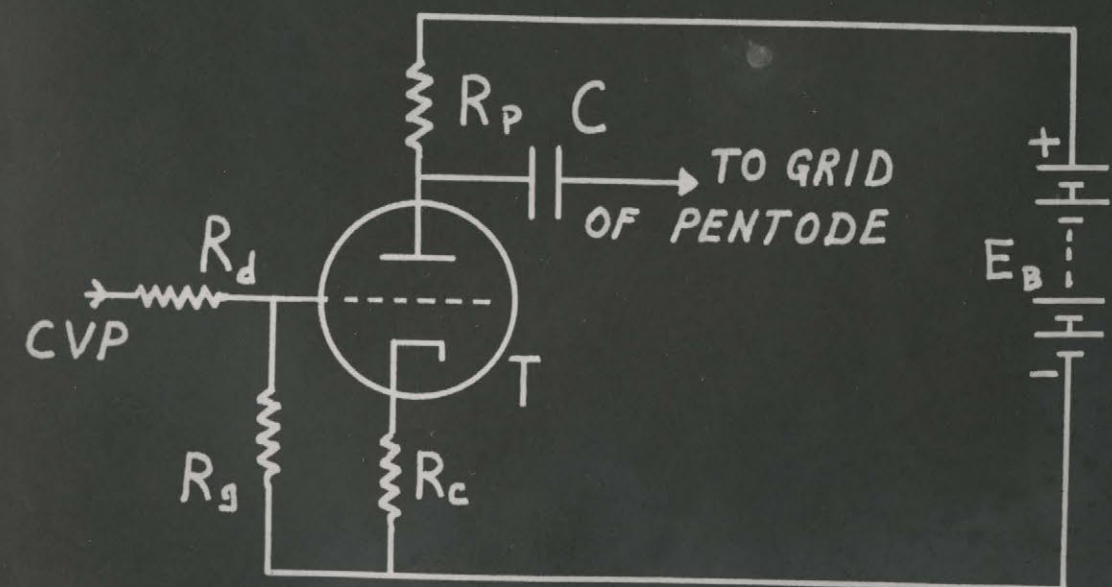
R_p	Mohms	0.1	1/2 watt
R_c	Mohms	2200	1/2 watt
R_g	Mohms	0.1	1/2 watt
R_d	Mohms	0.15	1/2 watt
C	pf.	0.01	450 V
E_B	Volts	300	
CVP	constant voltage pulse		

T - 6J5

PULSE GENERATOR

DIAGRAM 1
FOR LEGEND SEE OPPOSITE PAGE

PHASE SHIFT AMPLIFIER

DIAGRAM 6
FOR LEGEND SEE OPPOSITE PAGE

LEGEND FOR DIAGRAM 2

R_L	Mohms	0.1	C_k	pf.	2
R_{d1}	Mohms	0.33	C_1	pf.	0.004
R_{d2}	Mohms	0.47	C_2	pf.	0.0001
R_g	Mohms	0.5	C_{d1}	pf.	0.1
R_D	ohms	47000	C_{d2}	pf.	0.01
R_{c1}	ohms	1000			
R_{c2}	ohms	1500			

T_1, T_2, T_3 , are 6SJ7's.

All resistors are 1/2 watt. Condensers are rated at 450 V with the exception of C_c which is rated at 25 V.

RESISTANCE-CAPACITANCE COUPLED AMPLIFIER

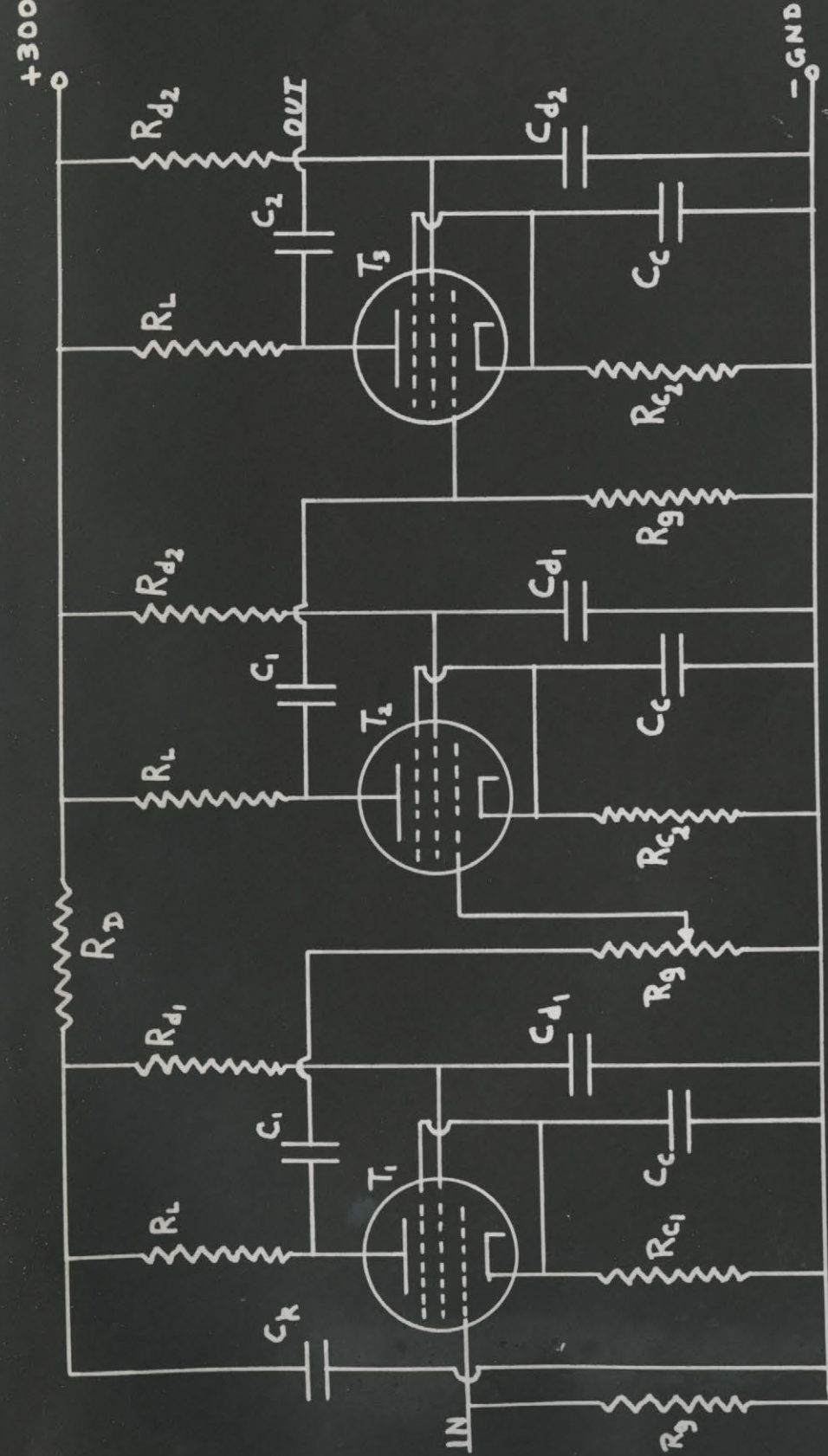


DIAGRAM 2
FOR LEGEND SEE ABOVE

LEGEND FOR DIAGRAM 2A

R_{D1}	ohms	47,000	C_{k1}	$\mu f.$	10
R_{D2}	ohms	18,000	C_{k2}	$\mu f.$	10
R_{L1}	Mohms	0.1	C_1	$\mu f.$	0.01
R_{L2}	ohms	82,000	C_2	$\mu f.$	0.05
R_{d1}	Mohms	0.33	C_{d1}	$\mu f.$	0.1
R_{d2}	Mohms	0.47	C_{d2}	$\mu f.$	0.01
R_g	Mohms	0.5	C_c	$\mu f.$	12
R_{c1}	ohms	800			

T_1, T_2, T_3 are 6SJ7

All resistors are 1/2 watt. Condensers are rated at 450 V with the exception of C_c which is rated at 25 V.

RESISTANCE CAPACITANCE COUPLED AMPLIFIER

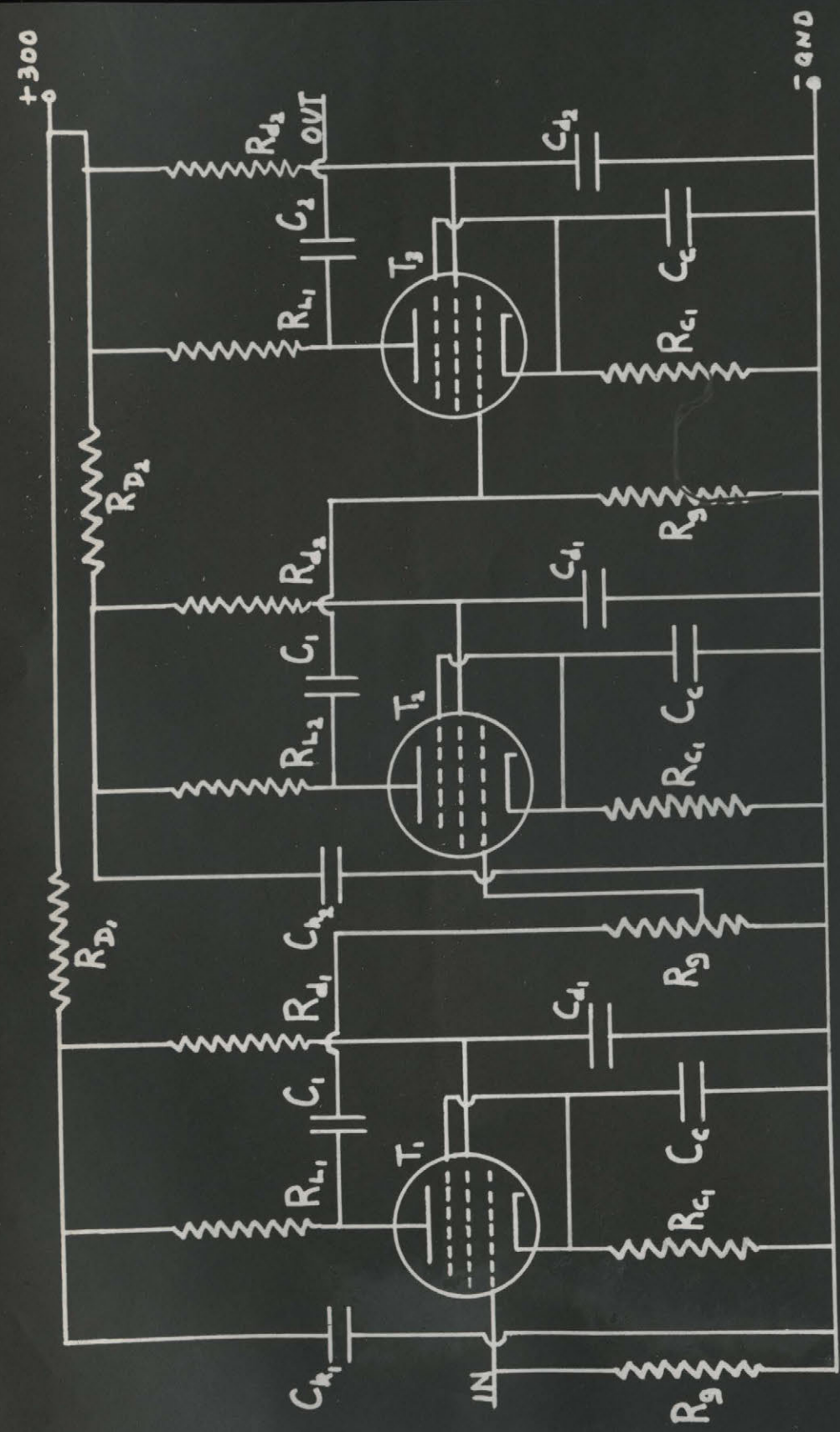


DIAGRAM 2A

FOR LEGEND SEE ABOVE

LEGEND FOR DIAGRAM 3

R_y	Mohms	1
R_p	Mohms	4.5
R_c	Mohms	0.2
R_b	Mohms	0.5
R_g	Mohms	0.1
R_d	ohms	47000
C_g	pf.	0.001
C_c	pf.	0.05
T_1	6SJ7	
T_2	2050	

LEGEND FOR DIAGRAM 4

R_L	Mohms	0.1
R_x	ohms	2200
T_3	6SN7	
D.P.	Deflection Plate	

All resistors are 1/2 watt. Condensers are rated at 450 v.

SWITCH CIRCUIT and AMPLIFIER

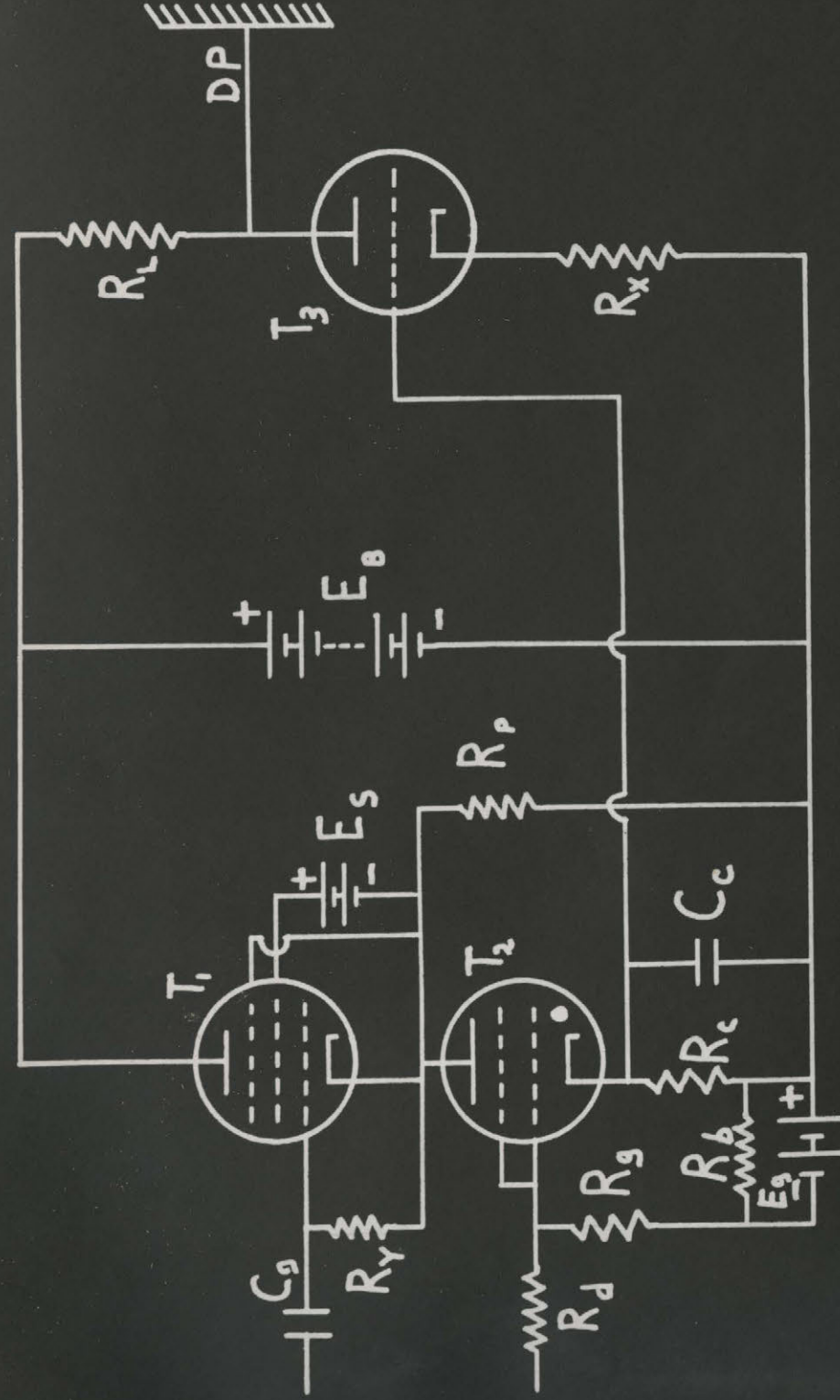


DIAGRAM 3
FOR LEGENDS SEE ABOVE

DIAGRAM 4

LEGEND FOR DIAGRAM 5

R_p	Mohms	2	C	$\mu f.$	0.02
R_s	Mohms	0.6	C_c	$\mu f.$	0.1
R_{c2}	Mohms	0.1	C_o	$\mu f.$	0.1
R_g	Mohms	0.5	T	884	
R_{c1}	ohms	270			

All resistors are 1/2 watt. The condensers are rated at

450 V.

CONSTANT-VOLTAGE PULSE CIRCUIT

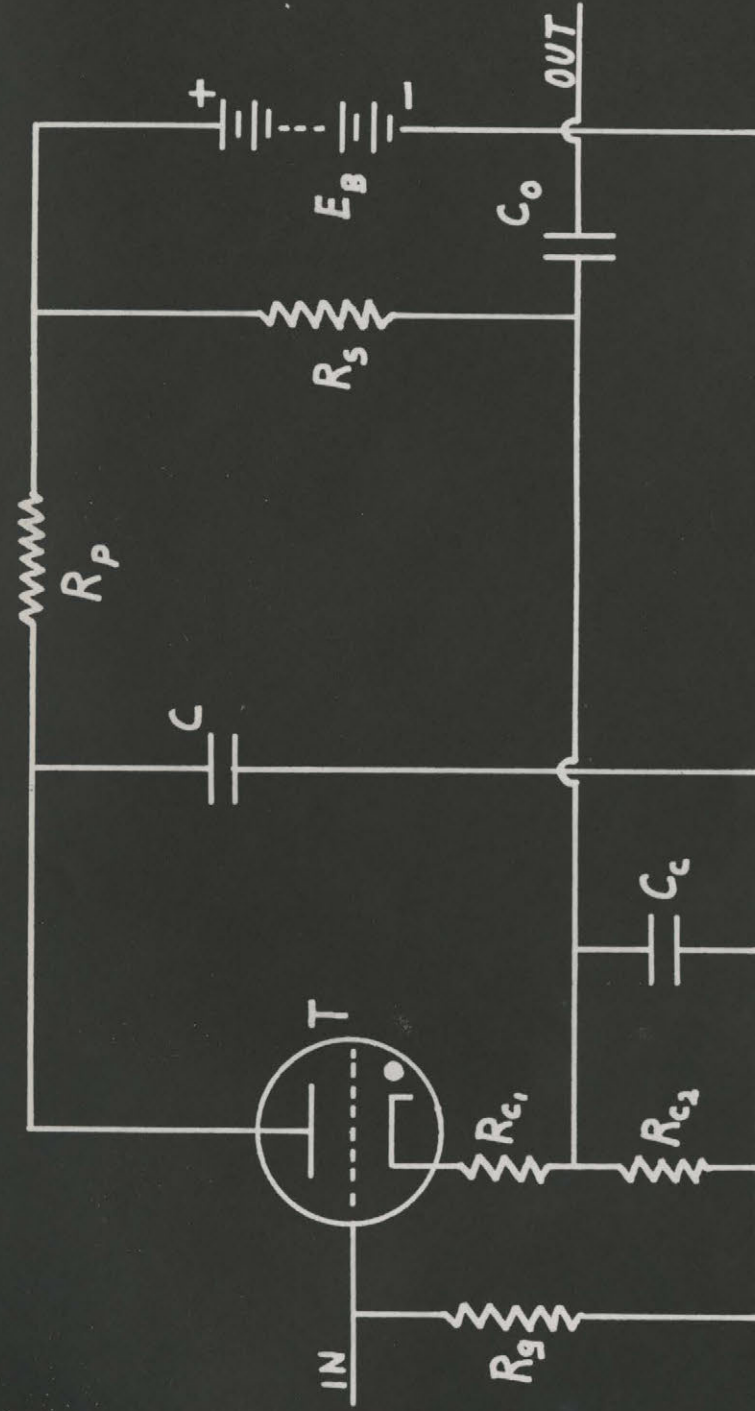


DIAGRAM 5
FOR LEGEND SEE ABOVE

LEGEND FOR DIAGRAM 7.

AA	audio amplifiers	VA	Voltage amplifier
G	pulse generator	S	source
Sc	switching circuits	R ₁ , R ₂	receivers
D	constant voltage pulse circuit	R _c	cut-off receiver
INV	CVP inverter	CRT	cathode ray tube

BLOCK DIAGRAM OF CIRCUIT

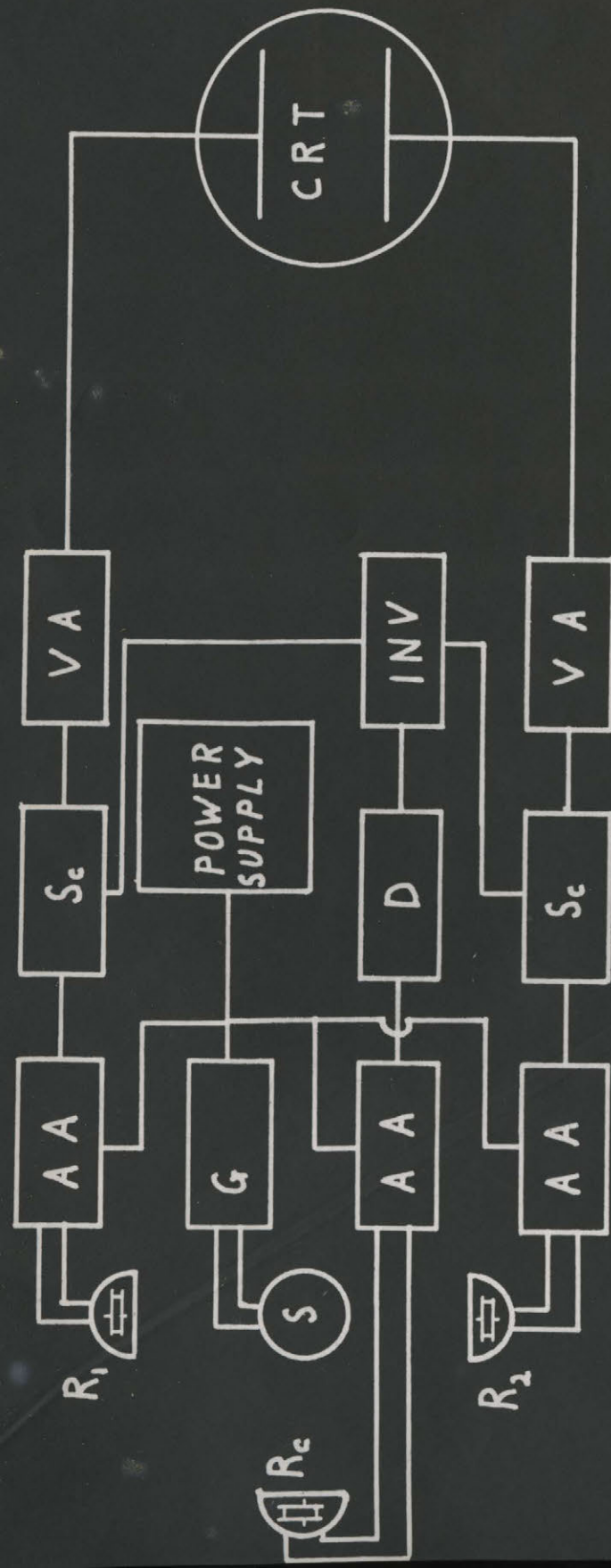


DIAGRAM 7
FOR LEGEND SEE ABOVE

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