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Final Report

EVALUATION OF A PHOTOELECTRIC RAINDROP-SIZE SPECTROMETER

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ABSTRACT

The photoelectric raindrop-size spectrometer is described, and details of the calibration problem are discussed. Sources of error are examined, and corrective procedures are set forth where possible. Operational characteristics and proposed improvements are outlined. Pertinent elements for consideration in producing an improved future model are presented in the final section.

OBJECTIVE

The objectives of the present research are to evaluate the performance of the photoelectric raindrop-size spectrometer, which was developed under the author's guidance with National Science Foundation support, to calibrate it for the observation of rain, and to make field observations and develop field techniques for use of the instrument to the extent possible under the subcontract.

EVALUATION AND CALIBRATION OF RAINDROP-SIZE SPECTROMETER PROTOTYPE MODEL

1. Description and Specifications

The instrument subject of this report is conveniently described as a photoelectric raindrop-size spectrometer. In broad outline, it is designed to observe rain or spray with a minimum of disturbance of the observed field. A schematic diagram of the entire instrument is given in Fig. 1.

THE DROP FIELD

The drop field is optically defined by the light beam and by the field stop in front of the photocell (Figs. 2 and 3). These field boundaries are designed to define a volume of about 6 cm^3 so that it is unlikely that more than one drop will appear in the drop field at any particular instant. Thus each drop produces a discrete light impulse as it enters the beam.

Obvious shortcomings of this scheme in a stationary field instrument are that it is capable of sampling only a small region at a time, that its count represents an areal distribution, and that it depends heavily upon the natural fall speed of the drops present. In the present instrument, a horizontal rotation is introduced so that in effect the sensitive field sweeps through space at a linear rate of 6 m per sec. This is done by mounting the light source and the photometer on arms which project from a rotating head. In this way the drops are viewed practically independently of fall speed; they are counted according to their volumetric distribution in the air, and the sampled volume is enlarged to some 3600 cm^3 per sec. These design figures were chosen with the intent to count drops down to the order of 50-μ diameter.

THE LIGHT SOURCE

A 6-v, 100-w ribbon-filament lamp serves as the light source. In this lamp, the filament measures about 2.0 x 0.2 cm. An anastigmatic lens of 3.125-in. focal length and with an f/-number of 1.7 forms a real image of the source at a distance of 10 in. from the lens. The resulting convergent beam provides an adequately illuminated field of which the photometer views a section limited by the photocell field stop (Fig. 3). The photometer optics are then adjusted to view the beam at a forward angle of 45°, and to focus the central plane of the beam in the plane of the photocell field stop. This provides a sharp

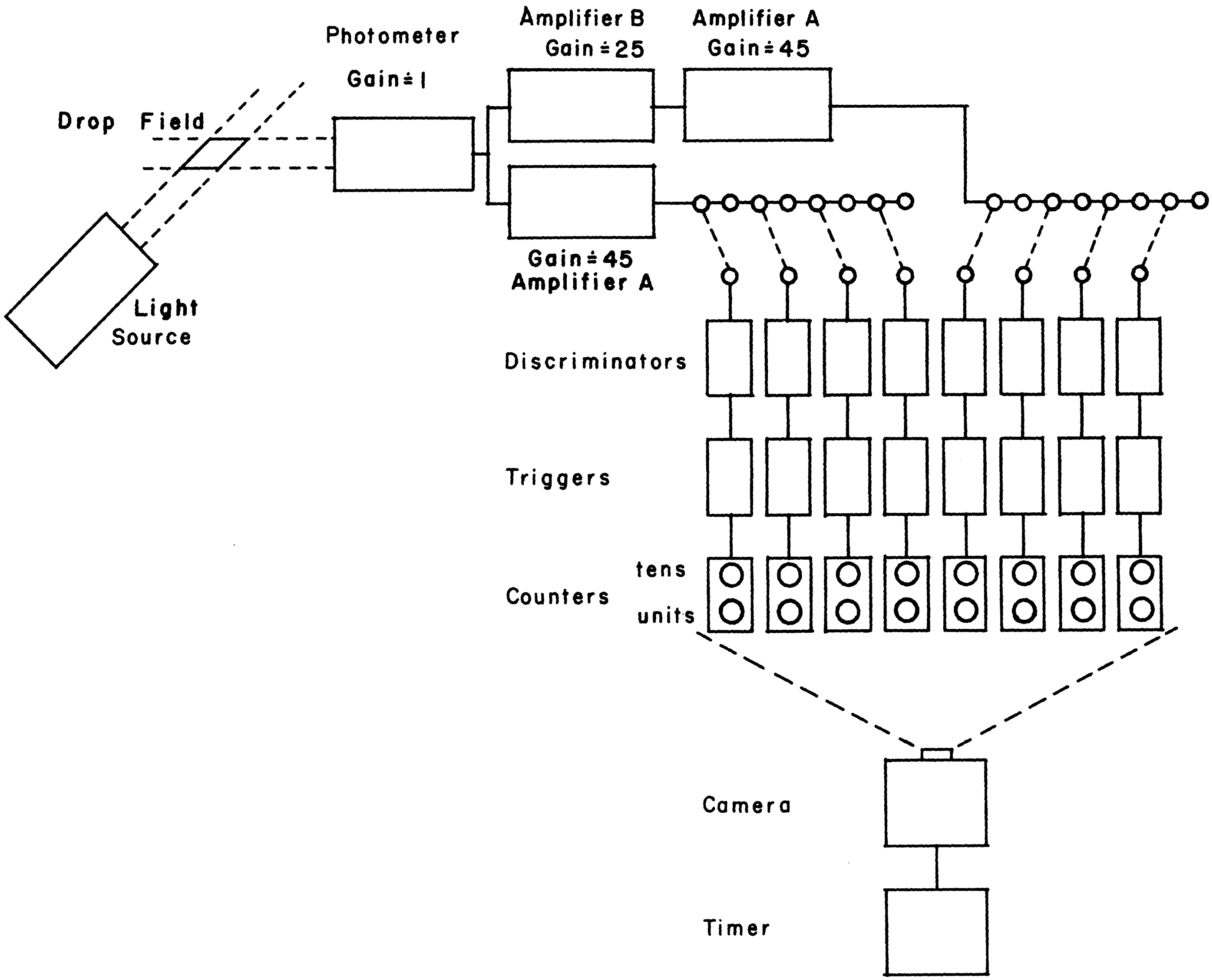

Fig. 1. Schematic diagram of the photoelectric raindrop-size spectrometer using a photographic recording system.

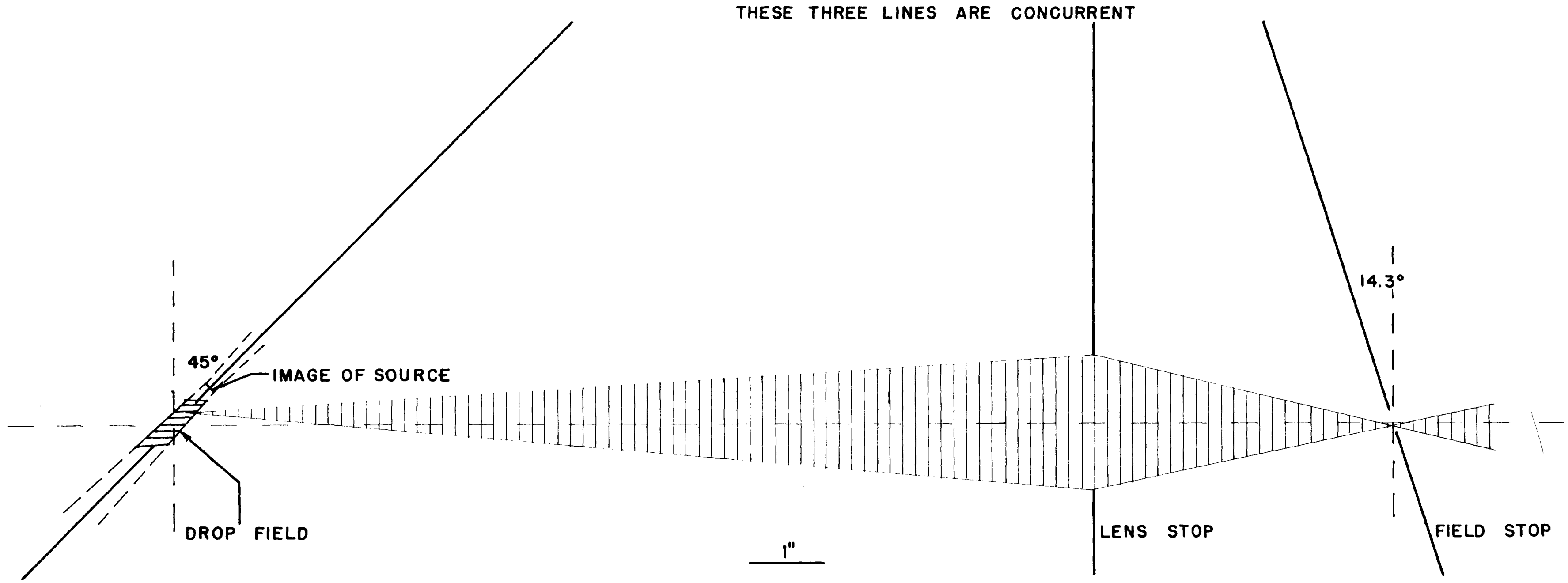

Fig. 2. Optical relationship of the light beam and the source image to the photometer as seen from above.

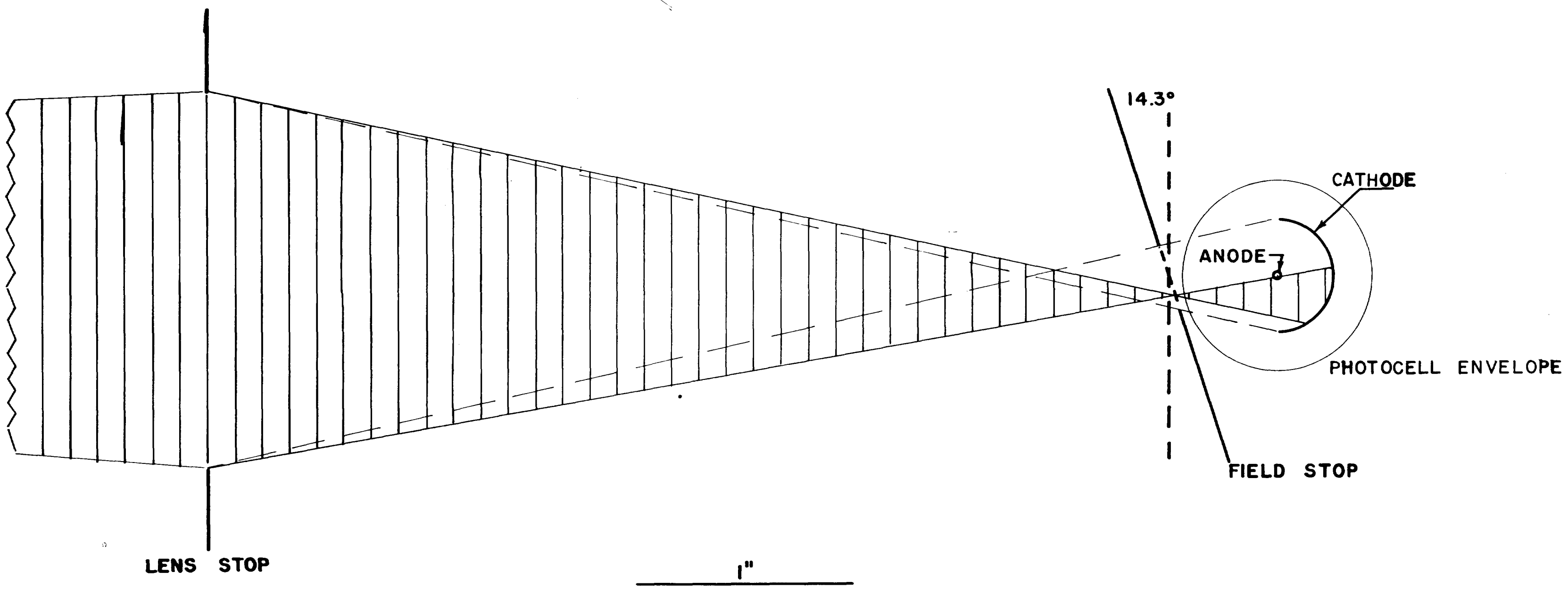

Fig. 3. Optical detail of the photometer showing relationships among the photocell, the field stop, and the photometer lens.

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boundary for the viewed field. At the same time it serves to spread the light scattered from objects in the viewed field over the cathode of the photocell, which is located 0.75 in. behind the field stop, giving relatively uniform sensitivity of the photocell to particles in all parts of the field.

THE PHOTOMETER-COUNTER SYSTEM

The present photometer uses a 921 photocell and a 38-tube preamplifier (Figs. 4, 5, 6), which are mounted together on one of the rotating arms. Power and signals are transmitted to and from the rotating elements by means of mercury pool commutators. Signals from the preamplifier are transmitted to a conventional pulse amplifier and thence via discriminators and suitable electronic triggers to an 8-channel integral pulse-height analyzer. Two glow-transfer tubes (Atomic Instrument Co.) are used for registering the counts in each channel. These operate continuously, providing a capacity of 100 counts. The count is recorded by photographing the counter panel at least once each minute.

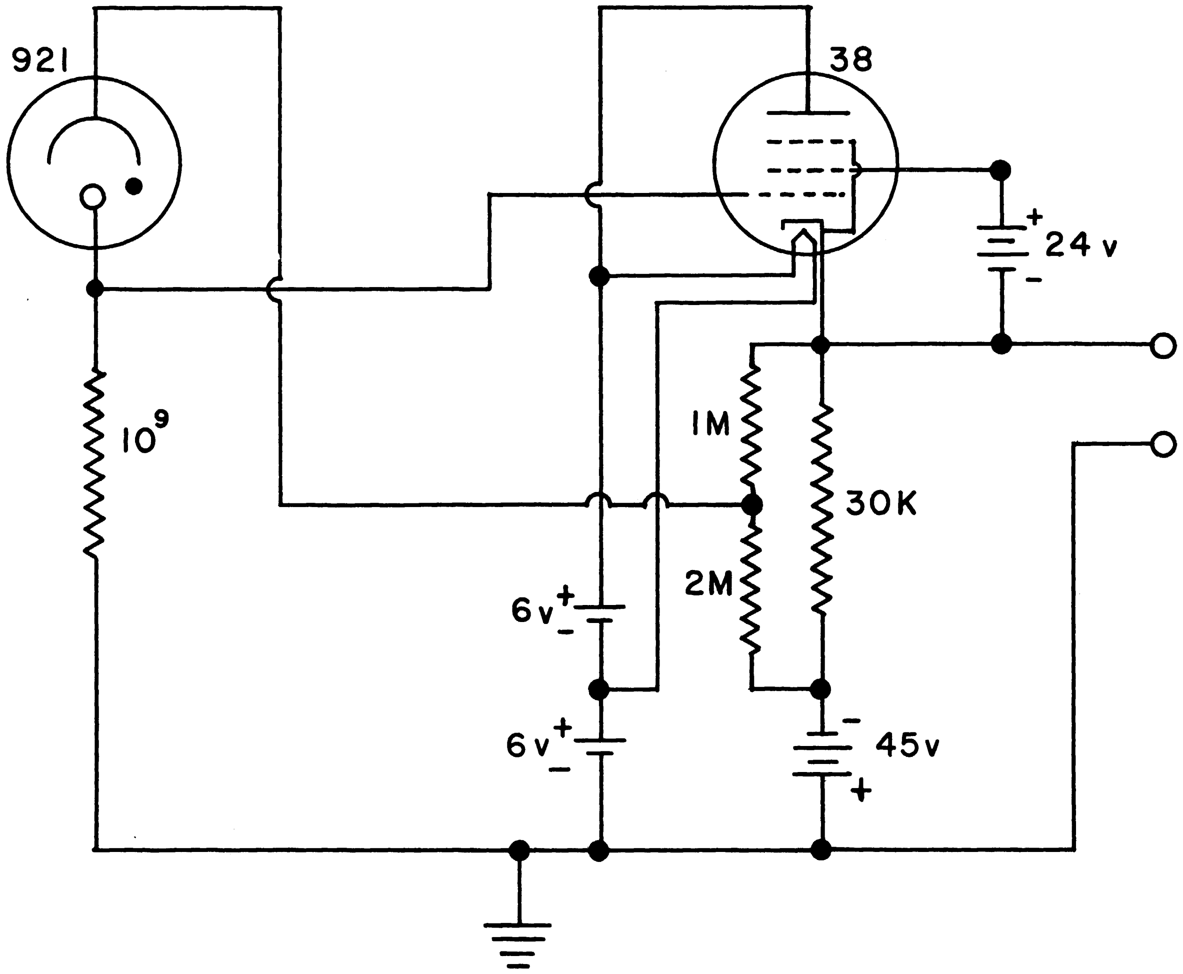


Fig. 4. The photometer circuit.

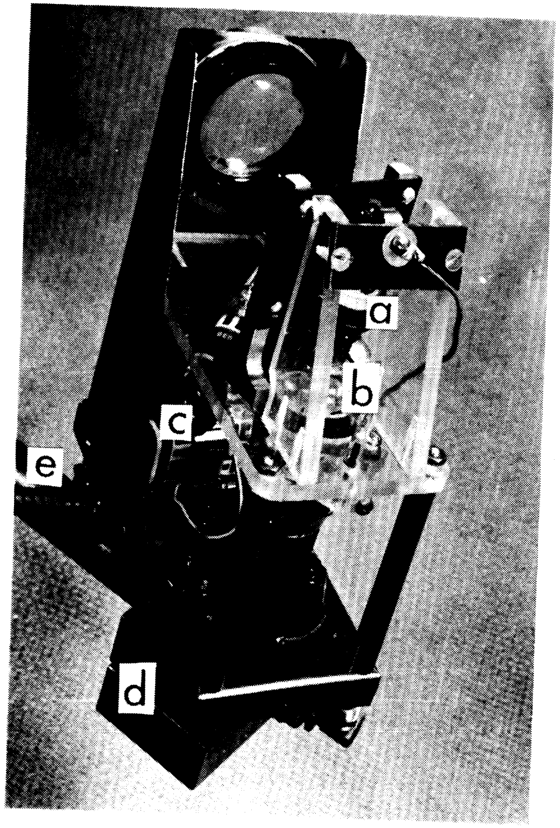


Fig. 5. View of the photometer with cover removed showing (a) 921 phototube in place, (b) 38 tube, (c) batteries for 24-v and 45-v supplies, (d) mounting clamp, and (e) support arm.

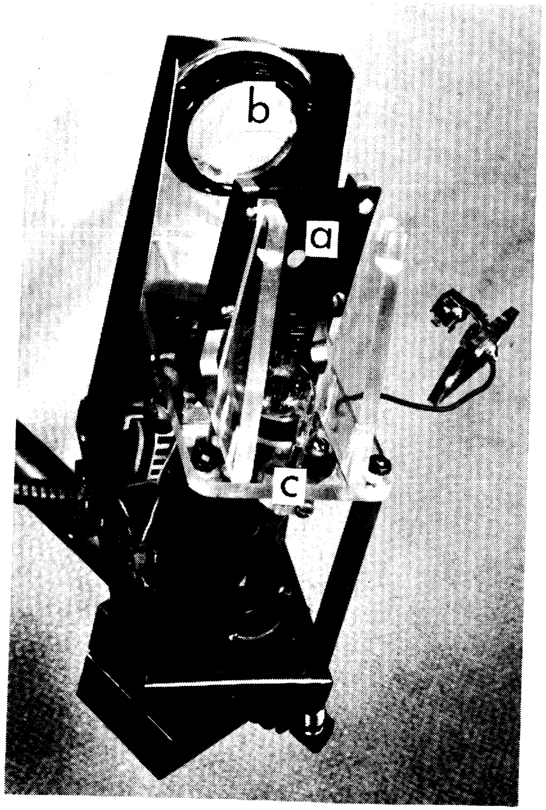


Fig. 6. View of the photometer with cover and phototube removed showing (a) field-stop aperture, (b) lens, and (c) 10^9-ohm Victoreen resistor.

THE LIGHT SHIELD

Because it is essential that the drop field be viewed against a uniformly dark background, a light trap has been constructed to provide such a background. This light trap serves adequately for all light conditions except that of direct sunlight. Because direct sunlight and rain coincide only rarely, it is not deemed necessary to take more elaborate light-shielding measures. The spectrometer is shown in place in the light trap in Fig. 7.

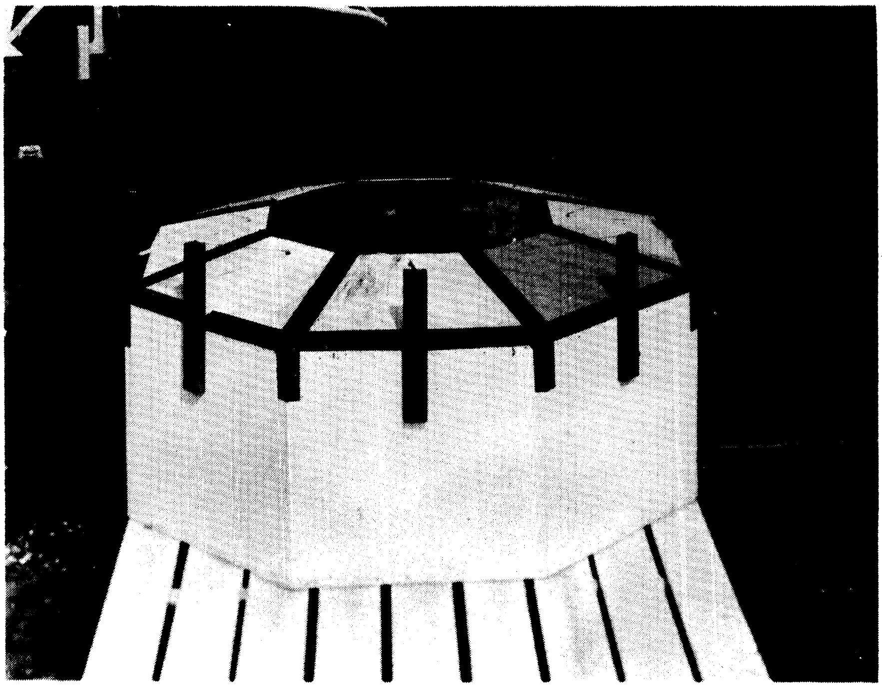


Fig. 7. View of the spectrometer in the light shield, ready for operation in rain.

2. Details of Calibration

In the process of accomplishing an adequate calibration of the instrument, it has become clear that the various components must be studied individually to isolate the variables properly. The arrangement for calibration using artificially controlled water drops is shown in Fig. 8.

THE LIGHT SOURCE, OPTICS AND BEAM CHARACTERISTICS

The ribbon-filament lamp is used in the present instrument for several reasons. Its principal advantages now appear to be (1) its low power re-

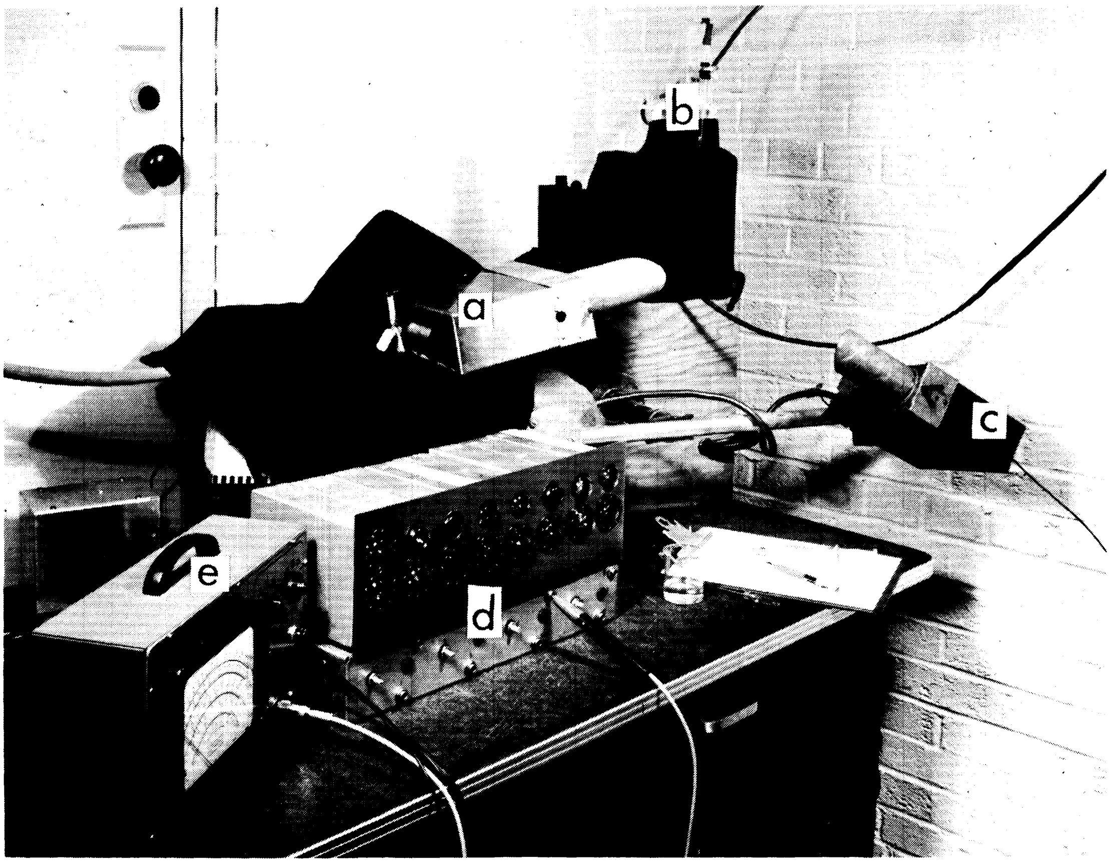


Fig. 8. Calibration setup in laboratory showing spectrometer head tipped up on mounting board. Objects are (a) light-source box, (b) high-voltage drop dripper, (c) photometer box, (d) counter panel, and (e) vacuum-tube voltmeter.

quirement (100 w), (2) its suitable shape, (3) its ready availability at modest cost, and (4) the relatively high optical efficiency, attained by using a convergent beam with an extended source of moderate intensity in preference to a collimated beam with a line source of very high intensity (as in the instrument of Mason and Ramanadham[1]). Among its disadvantages are (1) the considerable current it requires (18 amp at 6-v dc), (2) the fact that it is difficult to obtain with a pre-focus (bayonet-type) base, (3) the expansion-contraction wrinkle in the filament, which causes the image to focus at varying distances from the lens depending upon vertical position in the beam, and (4) the excessive thickness of the beam in the desirable (most uniformly illuminated) viewing area.

Early studies of the beam intensity, which were made using a photoelectric probe, mounted so that its position in a coordinate system fixed relative to the source could be recorded, first revealed the import of the third disadvantage cited above. It was found that although the photometer had been adjusted to view a suitable section of the center (vertically) of the beam, a section of the source image was included in the lower part of the field, resulting in an excessive gradation of light intensity across the field. As a result, the optical adjustment of the source was changed to move the image point out beyond the viewed area, and the beam intensity was mapped again. The result is shown in Fig. 9. Although the illumination is not strictly uniform, the variation is subject to compensation by any of several methods.

THE PHOTOMETER OPTICS AND PHOTOCELL CHARACTERISTICS

The photometer lens is identical with that of the light source. It is arranged to focus objects in the central plane of the beam in the plane of the field stop. The field stop, in turn, is designed to limit the view of the photocell to a circular field of 1-in. diameter. The shape of this field, at the central plane of the beam, is shown in Fig. 10 as determined by probing the field.

The probe used for mapping the photometer response was made as follows. A small bright strobe source was housed in an opaque cover and a hole 0.040 in. in diameter was drilled through the end of this cover. Initial tests were made with this probe, but it was found that the probe was highly directional. To meet this objection, a clear glass bead was selected for size and sphericity under the microscope and pressed into the opening already present. The directional effect of this form of the probe is not discernible unless it is viewed from far off-axis.

Another effect of some concern is that accountable to the shadow of the anode cast upon the cathode. The probe studies show this effect clearly (Fig. 10).

The optical axis of the photometer optics is carefully oriented to be tangent to the circle of revolution of the sensitive field. This arrangement assures that drops encountered by the field will be viewed essentially as spots with very little lateral movement. Hence the device is not sensitive to the "fore" and "aft" gradations of intensity of the beam. The edge effects are limited to those associated with the field-stop definition of the field and the statistical distribution of drops that are only partially seen or that move from the field without penetrating the most intense plane of the beam. The magnitude of this error is inversely proportional to the radius of the viewed field.

Consequently the only pertinent beam-intensity variations are those in the most intense (x, z) plane of the beam. These variations are depicted above (Fig. 9). Although these variations may be compensated very well by the use of a variable density filter at the field stop, it is also possible to correct for these and the sensitivity variations of the photocell cathode by application of simple correction factors to the accumulated spectral distribution figures. This is accomplished most simply by assuming that equal numbers of drops of each size will be seen in equal subareas of the viewing field taken normal to the optic axis of the photometer. Although this assumption somewhat

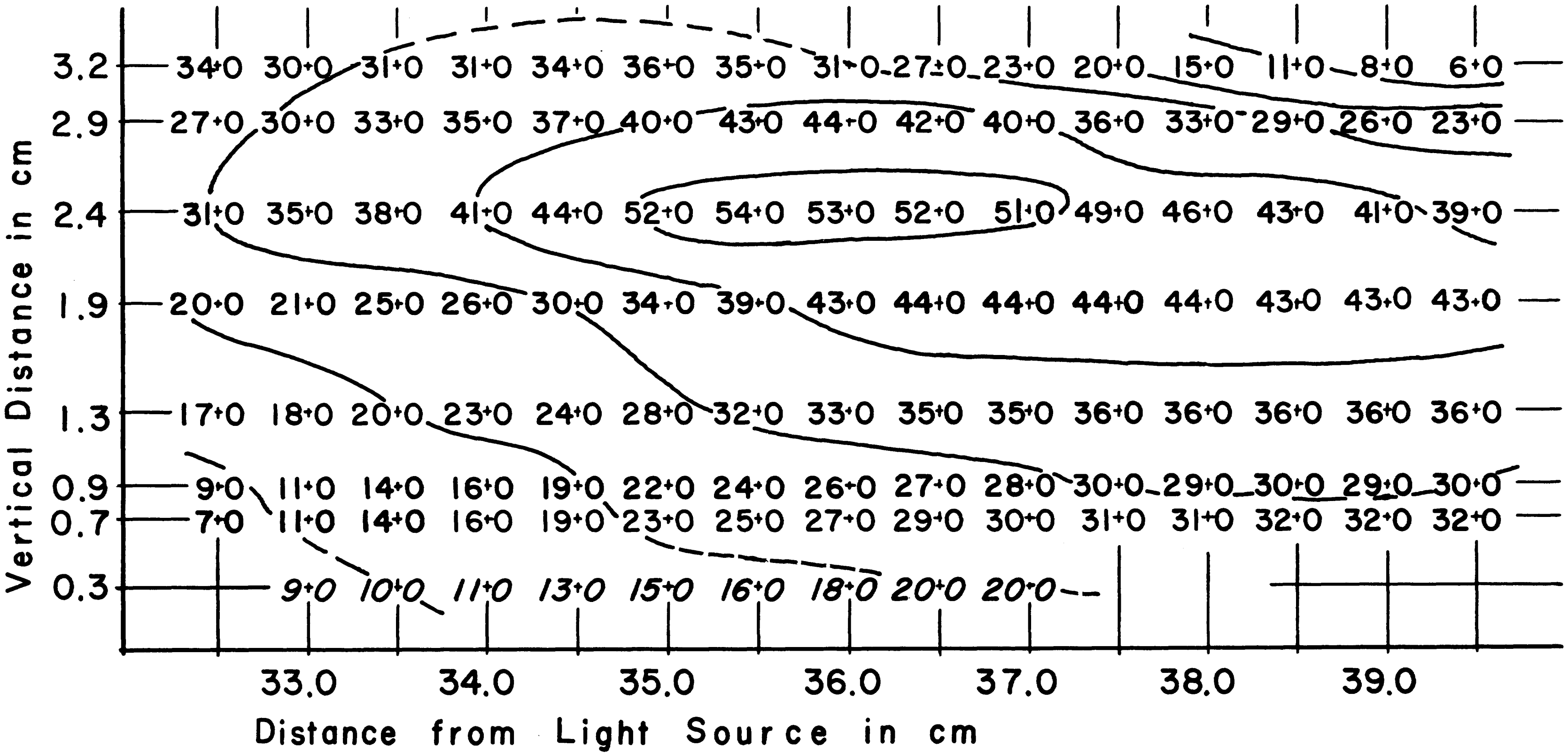


Fig. 9. Distribution of intensity of the light beam as determined using a photoelectric probe. Dashed lines and italicized figures are extrapolated.

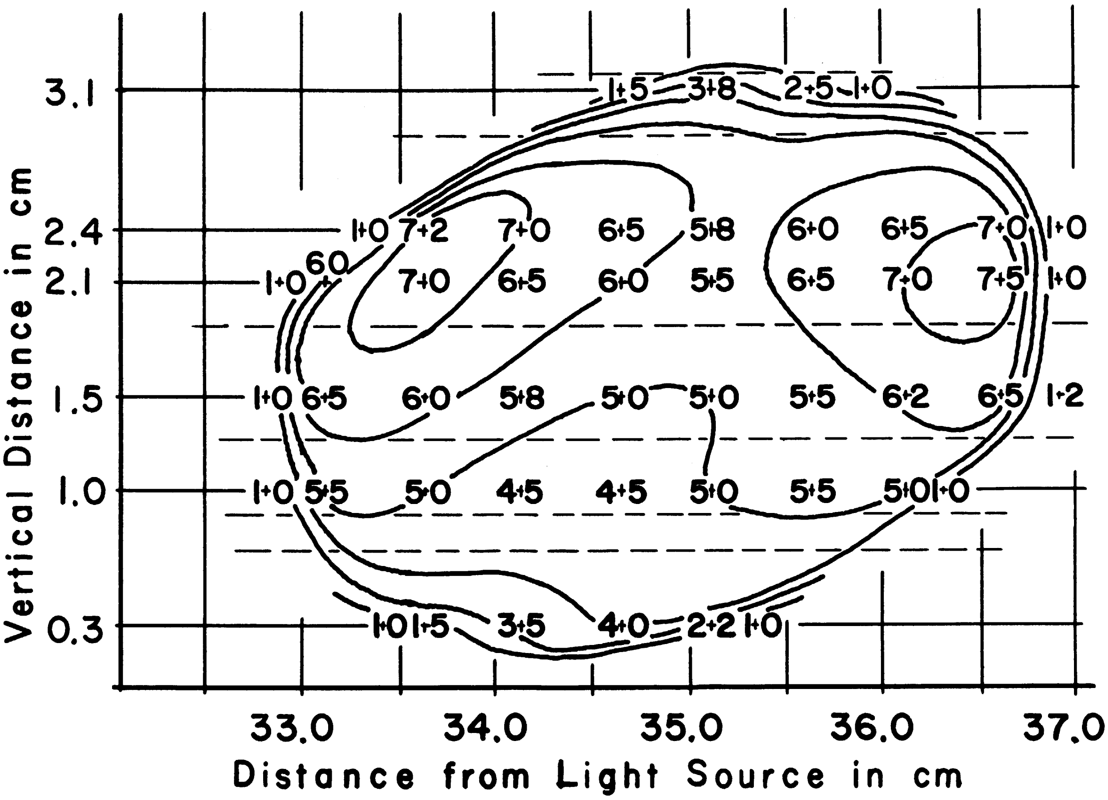


Fig. 10. Distribution of photometer responses to a constant intensity light probe in the central plane of the sensitive field.

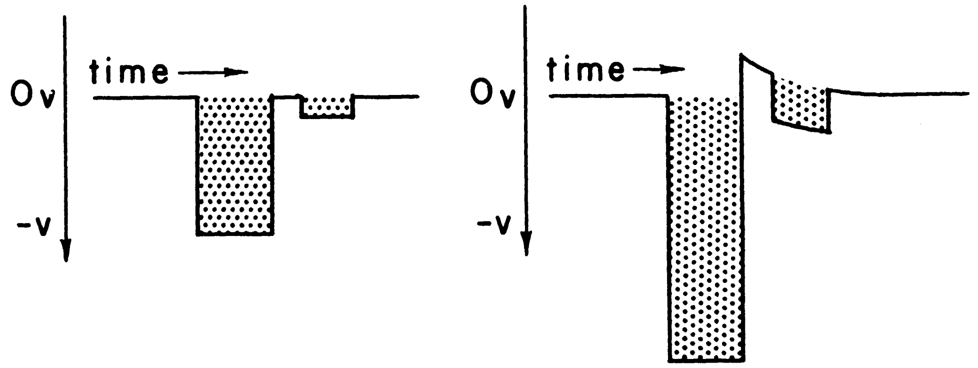
oversimplifies the problem, the correction obtained by this means renders the data adequate relative to available standards.

A rigorous test of this general approach was not possible within the limits of the present contract. Such a test could be made in a comparative experiment using an artificially reproducible spray. This experiment would provide for observation of drop spectra by at least two generally accepted methods (e.g., photographic and filter paper) in addition to the present one. The resulting comparison should make possible a complete empirical calibration of the spectrometer relative to the method accepted as a standard. The photographic method would appear to be more nearly absolute as regards volumetric spectra (as distinct from those obtained by catching drops on horizontal surfaces) than other available methods for relatively large drops.

THE ELECTRONIC SYSTEM

The photometer is designed around a 921 photocell and a 38-tube preamplifier, using a 10^9-ohm Victoreen resistor. The combination of the photocell and 38 tube operated for small grid current[2] in a cathode-follower-type circuit was adopted in preference to a photomultiplier. For high-speed light-pulse counting, a photomultiplier would be needed, but for the pulse sizes and rates anticipated here, the photocell and 38-tube-preamplifier combination has adequate sensitivity and is therefore preferred on grounds of simplicity and stability.

Following the preamplifier is an amplifying system designed to amplify the small negative pulses generated by the photocell. Since the pulses are randomly spaced in time and have a large yet random range of amplitudes, the amplifier must have good linearity, stable and adequate gain, and minimum generation of pulse overshoot. For example, if a large amplitude pulse is followed closely in time by a small amplitude pulse, any nonlinearity or overshoot of opposite polarity induced by the large pulse will be superimposed on the small following pulse, thus distorting its true magnitude. This is illustrated in Fig. 11.



(a) Incoming pulse sequence

(b) Amplified pulses showing overshoot distortion effect

Fig. 11. Sketch showing typical distortion of pulses attributable to large pulse overshoot.

Ideally, a direct-coupled amplifier might be considered because it is the only type which produces no pulse overshoot. Its susceptibility to output level drift, however, would seriously interfere with operation of the pulse-height-level discriminators which follow.

The above criteria were satisfied with the multistage amplifier indicated in the block diagram (Fig. 1). It incorporates both direct and resistance-capacity coupling and negative voltage and current feedback. The signal from the preamplifier is fed in parallel to two amplifiers. One has a stabilized gain of 45, the other a gain of 25. The 45X amplifier directly drives a set of pulse-height selectors and counters for the large pulses. The 25X amplifier has a pulse-height limiter in its output to prevent the large pulses from overloading the small pulse amplifier which follows. The small pulse amplifier with a gain of 45 feeds the second set of pulse-height discriminators and counters. These counters count all pulses, both large and small. By properly adjusting the pulse-height discriminator levels, one counter counts all pulses, the next counts all but the smallest size group, and so on up to the largest size category of pulses which is accumulated by the last counter. Simple subtraction then suffices to sort out each class or range of pulse amplitudes.

Amplifier gains and operating points, limiting levels, and discriminator biases are all selected to optimize the pulse-amplitude counting accuracy of the system.

Each pulse-height discriminator has an adjustable bias control to permit selection of the drop-size range for its counting channel. The output of the discriminator drives a novel type of univibrator which was developed by Mr. Norman Seaton of the University of California at Berkeley. This univibrator is sensitive to very small signals, and so is capable of functioning both as a counting trigger and a pulse shaper. The resulting circuit simplification is helpful.

The scaling and registering circuits are adapted from those suggested for use with the glow-transfer scaling tubes (Atomic Instrument Co.).

THE COUNTERS AND READOUT TECHNIQUE

It is clear that a wide variety of counting and readout schemes can be used for a system such as this. Once the photometer response is shown to be capable of giving the desired information, the matter of specific counting and readout technique is determined as a function of the desired form of the data as balanced against the cost. Ideally, the spectrometer would print out the counts periodically and reset to zero. Actually the present instrument uses a much less expensive, but also less convenient, readout method.

The method settled upon for the prototype instrument uses photographic compilation of the record of counts as the simplest and least expensive readout technique available. The selection of the particular counters was partly dictated by this choice, and partly by the requirement of a moderate counting speed. The glow-transfer tubes combine the necessary speed (2,000 counts per second) with the photographically convenient bright spot indication of the count. Although mechanical counters would have been fast enough to serve as decade counters (using the glow-transfer tubes for unit counters), it was decided to use glow tubes throughout to simplify the photographic recording problem. Thus two glow tubes are used for each size category, one for units and the other for tens.

The recording period was arbitrarily set at one minute. Upon inspection of existing raindrop spectra and figures on space density of raindrops, it appeared clear that no single channel of the present instrument would accumulate more than 99 drops in one minute. On the other hand, if minute-by-minute resolution of the size spectra were available, the sequence might well prove to be highly interesting, and less detailed time resolution can always be obtained by combining spectra for successive minutes.

ERRORS

It has not been possible within the limits of the present study to make a complete evaluation of the errors of the system. Some have been discussed briefly above; some are indeterminate; but it appears that reasonably good compensation can be made for the large proportion of the error of the instrument. Below, the individual sources of error are examined in some detail, and methods of compensation are proposed.

i. Edge Effects.—Such edge effects as are present are entirely optical in nature. Any effect of the diffusion of the edges of the light beam has been eliminated except for those rare drops that might enter the viewing field but fail to penetrate to the bright central portion of the beam before falling out of the viewing field. The likelihood of this occurring is already small, but it can be reduced further by (a) increasing the translational speed of the viewing field, and (b) using a thinner beam (measured normal to the plane of Fig. 9).

The width of the beam (vertically) is sufficient so that beam-edge diffusion is mostly eliminated by the field stop.

The edge effect remaining, therefore, is that at the periphery of the field as defined by the field stop. This is approximately proportional to the inverse of the field diameter (circumference/area), and may therefore be reduced in future models by increasing the field size. A substantial improvement by this means appears to be optically feasible although other considerations tend to limit this direction of development. As indicated by the light-probe studies of the photometer response (Fig. 10), the edges of the field are very sharply defined by the field stop.

ii. Discrimination.—It was assumed that a small error would be present in the present device because of possible difficulty in obtaining absolutely sharp discrimination between successive counting channels. Tests were made to determine the width of the presumed transition zone using artificially generated pulses to define the thresholds between channels. It was found that this transition zone was in all cases so small that its determination depends upon the accuracy with which the oscilloscope can be read. This is less than 0.1 of the channel width in most cases and corresponds to an error of 2% in pulse height. Table I shows the specific figures for one setting of each channel.

TABLE I. DISCRIMINATION ERROR FOR ONE SETTING OF THE DISCRIMINATORS

Channel No.	Threshold Values		Error		
	Drop Diameter µ	Pulse Height mv	Pulse Height ± mv	Drop Size ± µ	Drop Size ± %
1	1000	280	5	8	0.8
2	1300	480	5	10	0.8
3	1600	720	10	13	0.8
4	1900	1020	20	20	1.1
5	2200	1370	20	18	0.8
6	2500	1760	20	18	0.7
7	2800	2210	50	32	1.1
8	3100	2710	50	38	1.2

iii. Light-Intensity Variation.—The pulse height produced by the photometer in response to a raindrop depends upon the maximum intensity of light encountered by the drop while it is in the viewing field. In all but a few exceptional cases (cited above in Section i), this intensity will correspond to the bright sheet of light near the central vertical plane of the beam. The distribution of light intensity in this plane is shown in Fig. 9. The variations of light intensity across the viewing field can be corrected for by making appropriate adjustments. Assuming that the raindrops that are observed are distributed uniformly throughout the viewed field, and that the intensity field is described accurately by the isopleths of relative intensity shown in Fig. 9, a suitable up-grading of the total counts can be made to compensate for the variations of illumination of the field. This implies that the calibration is based upon pulses which correspond to drops penetrating the brightest part of the field. Care is necessary to assure that this is so in determining the primary calibrating pulse height. All others may then be obtained artificially by using a pulse generator of suitable characteristics and adjusting the pulse height from one threshold to the next by means of the rule that the photocell response is proportional to the square of the drop diameter. This proportionality has been studied and found to hold very well for a broad range of drop sizes (60-µ to 2000-µ diameter). The curve of drop diameter versus photometer pulse output is presented in Fig. 12. The shape factor (see Section vi below) enters for large drops.

iv. Photocell Sensitivity.—Figure 10 shows the distribution of photocell sensitivity as it is revealed by the response of the photometer to a constant intensity, flashing light probe in the central plane of the sensitive field. A small strobe light, masked but for an opening of 0.040-in. diameter stopped with a clear glass bead, was positioned at numerous points in the central plane of the sensitive field. The photocell responses are plotted in Fig. 10 so as to show variations of the photocell sensitivity as a function of object

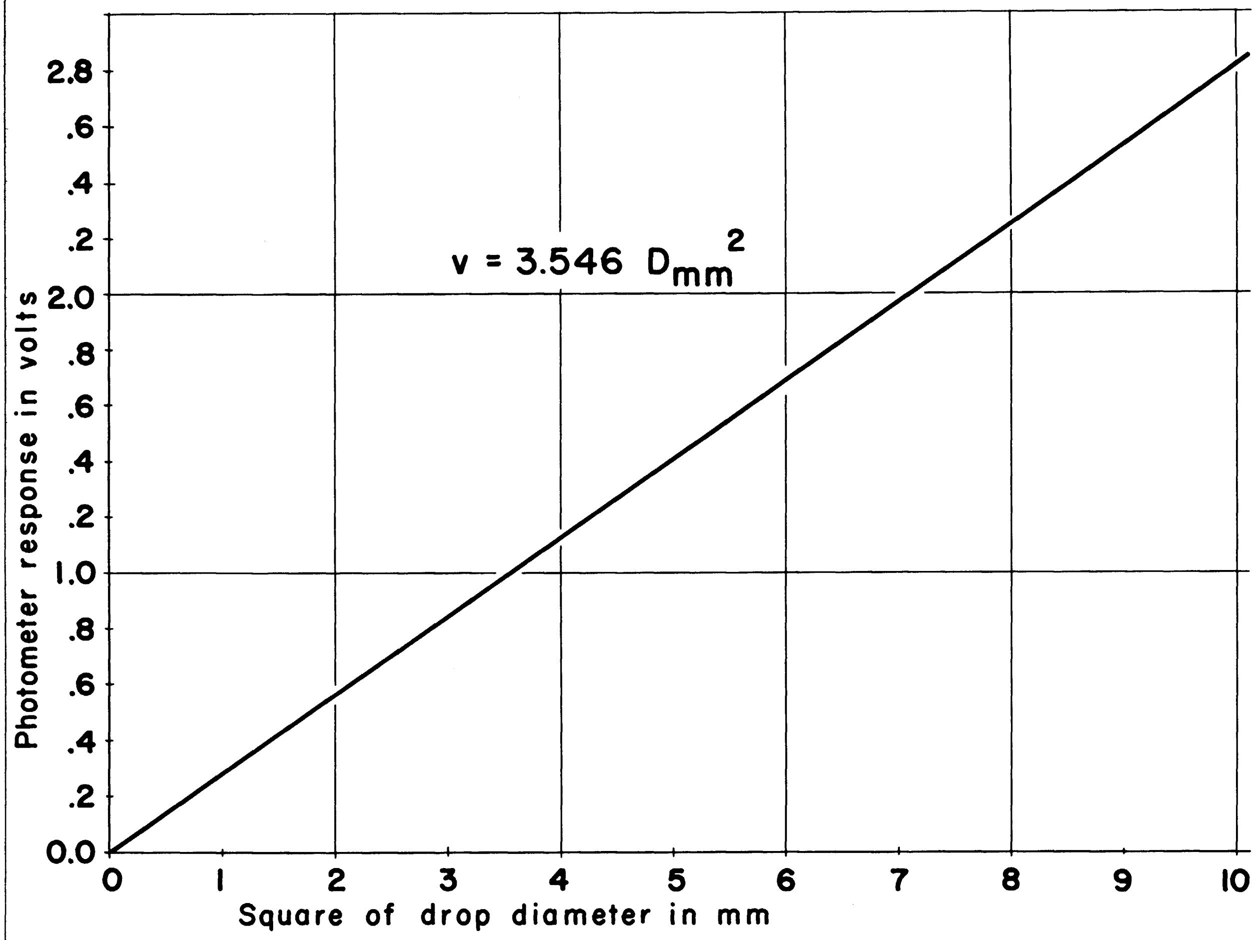


Fig. 12. Curve of drop size against photometer pulse output.

position in the field. These then indicate the variations of photocell sensitivity, and also the edge effects at the periphery of the field (see Section i above). Adjustment for these distortions can be made exactly the same way as those for light-intensity variations (Section iii above). In fact, the most efficient way of applying corrections for variations of light intensity, photocell sensitivity, and edge effects appears to be to combine them into a single adjustment pattern to be applied to totaled spectra. Figure 13 combines these variations in a composite map of the sensitive field.

v. Electronic and Microphonic Noise.—The electronic noise of the system, exclusive of microphonics, is well below the level of any signal that needs to be counted (i.e., that from a 60-μ-diameter drop). Microphonics create a more substantial problem.

There are two likely sources of energy to generate microphonics. These are the air blast used to keep the lenses dry, and the mechanical rotation of the instrument. Either of these energy sources is capable of causing vibration of sensitive and insufficiently supported parts of the photometer. There are obviously several remedial steps that can be taken. As of the present report, the photometer structure has been made as firm as possible, and the

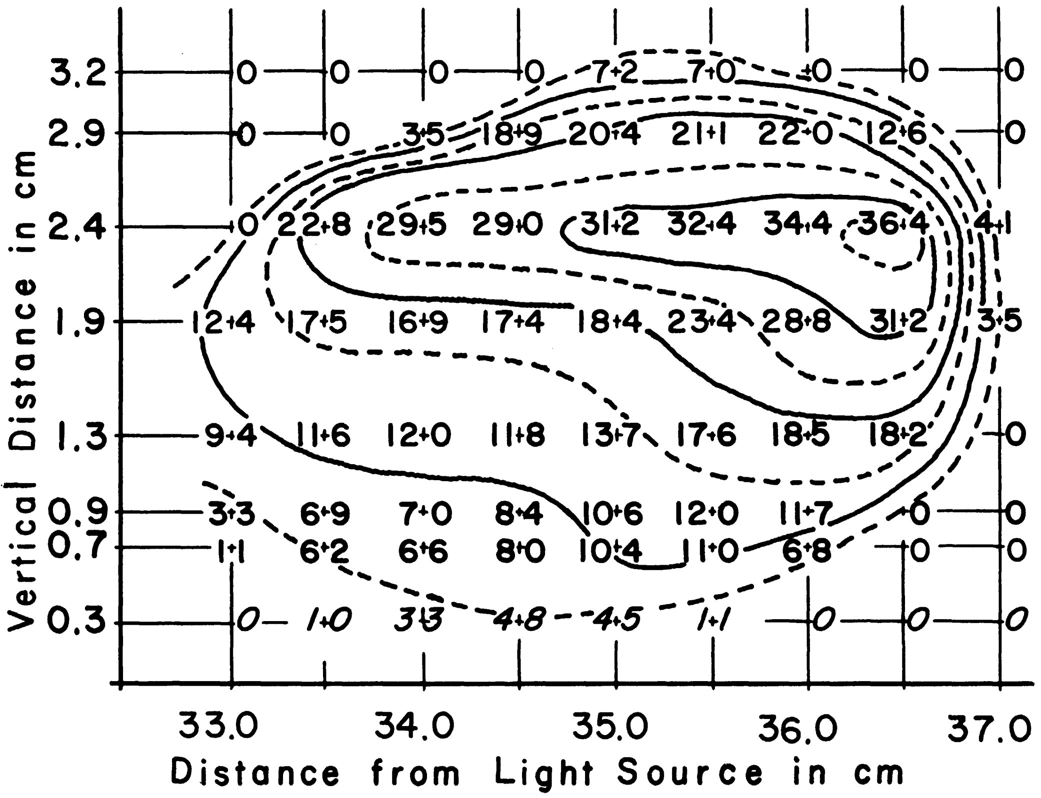


Fig. 13. Composite map of the sensitive field showing the distribution of the product (light intensity x photometer response), values taken from Figs. 9 and 10.

air blast has been studied experimentally and reduced so that it generates very little noise although it still fulfills its purpose. The present noise level with the instrument in rotation and the air blast on is 0.5 mv, corresponding to a drop size of 30-μ diameter.

There remain at least three obvious remedial measures that will be taken. These are (1) replacement of the 38 tube by a more modern tube of much better microphonic characteristics, such as the 6788 or the CK6247, (2) replacement of the present bearings by precision heavy-duty ball bearings, and (3) improvement of the dynamic balance of the rotating head. It appears reasonable to estimate that these measures will reduce the microphonic and electronic noise level to 0.2 mv or less, corresponding to a drop size of 20-μ diameter.

vi. Drop-Shape Factor.—Although it is well known that large drops tend to vibrate as they fall, and hence that they do not retain a spherical or nearly spherical shape, the present instrument depends in principle upon the counted drops scattering light as spheres. The fact that large drops vary from spherical form as they fall will cause them to scatter varying amounts of light to the photocell, and thus to be counted in the wrong size category. No evaluation of this error has been made. An empirical evaluation would appear to be a reasonable possibility, and will be made as further work with the instrument develops.

It is obvious that the probability of a drop being counted in the wrong size category is a function of the narrowness of the affected size categories. If these are broadened as the size becomes larger, the error of counting would be reduced. Obviously, the specific use for which the spectra are needed will dictate the conditions for this determination.

A reasonably direct evaluation of the signal range produced by monodisperse large drops can be made by manufacturing such drops and photographing the preamplifier output as shown by oscilloscope traces. This method would yield the statistical distribution of signals corresponding to a predetermined size of vibrating drop, and would thus make statistical criteria available for adjusting the routinely recorded drop spectra.

Obviously the effect worsens as the drops become larger; however, if a large drop category such as "3-mm diameter and larger" is used, and if the next smaller category is not excessively narrow, the corrections need not be too serious a problem. Vibrations of drops smaller than 2-mm diameter, for example, will produce much less drastic shape changes than those of the large drops.

vii. Turbulence Generated by Rotation. The boxes which cover the light source and the preamplifier of the present instrument are certain to generate considerable turbulence as they swing through the air. This turbulence should be much less effective on large drops than on small ones because of their inertial differences. Tests with a coarse spray show no visible deviation of the spray by turbulent eddies. In fog, however, the disturbance is clearly evident.

It is certain that this turbulence affects the observed field in part of each rotation. On the other hand, the natural wind field, and the vertical motion of the raindrops themselves, combine to reduce the effect of this turbulence on the drop counts to a small value. The natural wind sweeps continually across the observed toroid, transporting eddies generated by the rotating boxes downwind. There is small probability of these eddies affecting the viewed field except for a small element of arc of the toroid.

As for the distorting effect that the turbulence might have upon the drop spectra, it may occasionally produce coalescences between small droplets, but this effect would introduce only negligible error. It does not appear that this turbulence could systematically either increase or decrease appreciably the number of drops in any particular category of sizes larger than 100-μ diameter.

Improved aerodynamic design of the instrument head is an obvious remedial measure that should be taken. This will be done in future models and in modification of the present instrument as its development proceeds.

3. Operational Characteristics

To date the raindrop spectrometer has not been used extensively for obtaining field measurements. The stability of the instrument appears to be reasonably good although several features would be subject to improvement in later models. Statements in this section, therefore, represent predictions which are based in part upon laboratory experience with the instrument and in part upon anticipation of difficulties which might be encountered.

FIELD CALIBRATION

As pointed out above, there exists no absolute method for obtaining raindrop-size frequency distributions from the identical space sampled by the raindrop spectrometer. Thus comparison with observations made by the use of other methods can result only in a relative and nominal calibration evaluation. It therefore remains to devise a means for field checking of the spectrometer calibration which can be adequately proven. Two distinct techniques have been under consideration.

The first of these requires a system whereby a shower of a known drop-size spectrum may be made artificially at will. It is questionable whether the scheme is workable outside the laboratory. On the other hand, for laboratory testing of the instrument, this appears to hold considerable promise, and is one of the tests proposed for the laboratory testing phase. The advantages of this procedure are that the standard of comparison is absolute and the evaluation is direct. Problems which remain unresolved to date are those associated with the continuous production of uniformly sized drops, and with the development of an apparatus that will supply the drops uniformly distributed in a space somewhat larger than the sampled space. In addition, it would be desirable to have the artificial drops fall through the field at or near their terminal fall speeds. This requirement demands some distance of fall, which in turn introduces some problems of evaporation and of control of the drop trajectories. Nonetheless the method appears sufficiently workable to justify development. The proposed approach is to set up a series of individual drop drippers distributed above the circle of revolution of the field. The test would be monitored by the use of an oscilloscope camera in addition to the counters. The resulting photographic record would then be checked against the built-in sequence of drop sizes as well as against the totaled counts. This would constitute as nearly an absolute check as possible because it would be evident from the film if a particular drop missed the field or encountered only its edge.

The second technique involves the use of a set of glass beads. The beads have obvious advantages over water drops for field use, but our experience suggests that caution must be exercised to avoid spurious results. For example, the glass beads tend to accumulate some scratches in use. These obviously affect their light-scattering characteristics and spoil them for test purposes after a little use. There are additional problems involved in getting the beads to follow any predetermined flight path (because they tend to bounce from the walls of most launching devices) and in presenting them in a relation to the sensitive field that closely approximates the behavior of rain. These have not been entirely overcome, but workable solutions appear possible in future development.

DIRECT-CURRENT SUPPLY

It is essential that the light source and the filaments in all the amplification stages be supplied by constant sources as nearly as possible. In the light-source supply, a-c ripple is immediately apparent as oscillating intensity of the source. Obviously when such voltage variations are applied to the filaments of the amplifier tubes, varying amplification ratios are obtained. In either case, the variations are not tolerable. For the present instrument, it was decided that the simplest way to obtain a suitable 6-v, d-c supply was to use storage batteries. The constancy of the battery voltage is judged adequate for the filament supply, but in the case of the light source, which draws 18 amp, there is an obvious risk that the battery voltage may fall off in the course of a run several hours long. In the present model two heavy-duty storage batteries, providing a 400-amp-hr rated capacity, are used in parallel to supply the light source. Thus for testing procedures in which the source is not used for more than 6 to 8 hr, the supply is relatively constant.

In field use, depending on the situation, the stability of this source can be improved by either of two methods. The first and more obvious method is to use a larger bank of batteries hooked in parallel. The alternative method is to use a carefully filtered power supply capable of providing the required current without ripple (that is, with ripple amplitude reduced to that of the noise of the system from other sources). Depending upon the field situation as regards the availability and reliability of public electric power, such a scheme may prove to be more satisfactory than the battery-supply scheme.

In any event, since conventional methods exist whereby an adequate supply of stable voltage can be procured, this is not considered to be a serious developmental problem. Even under variable voltage conditions, it is possible to monitor the light intensities by means of a second photometer against which the drop pulses would be compared.

LIGHT SHIELDING

In the simplest form of the instrument, namely that in which a single phototube views the drops in a field illuminated with constant intensity light, it is obvious that the phototube must "look" at a constant intensity background. For this reason, as stated earlier, a light shield has been built for the present model. It was deemed a much simpler solution to build the light shield than to solve this problem by monitoring the background using a second photometer. Actually, the light shield is eminently successful under the diffuse light conditions that normally accompany rain. Under direct sunlight, the background light intensities vary with direction so that when the instrument rotates, the background signal, which forms the baseline from which pulses are measured, oscillates. This effect also could be compensated electronically, but it is not considered to be serious because of the relative infrequency of occurrence of direct strong illumination in the presence of rain.

4. Potential Improvements and Refinements

The present instrument has evolved as the results of numerous minor experimental tests became available. Its design and construction have been held to a minimum of expense because its builders have maintained the view that, *in toto*, it constitutes an experiment, and as such should serve mainly to supply information to provide a basis for the design of more completely satisfactory models in future. The following items point out the more obvious ways in which a second model would be improved over the prototype.

INCREASED VOLUME RATE OF SAMPLING

For some purposes, such as the correlation of rain spectra with radar echo details, it is desirable to observe large drops especially, whereas the small ones may be ignored. Because large drops occur relatively infrequently, it is necessary to monitor large volumes of air to construct sufficiently detailed time series of the drop spectra. It is probable, therefore, that for use with weather radar, it is desirable to increase the volume swept out by the sensitive field of the spectrometer, and to reduce the spectrometer sensitivity somewhat. Reduction of sensitivity would contribute to stability and would simplify other problems; hence it requires no further comment at this time.

The volume rate of sampling can be increased by altering either of two characteristics of the instrument. One of these is the linear speed with which the viewed field sweeps the rain field. The limits on this speed will be dictated by such problems as lens-wetting and the speed with which the natural rain field recovers from the physical passage of parts of the spectrometer structure. On the basis of experience to date, the speed can be doubled or trebled. Using physical modifications of structure and streamlining of members that can disturb the field, it is conceivable that a much higher speed could be attained.

The second characteristic that might be changed to increase the volume rate of sampling is the lateral area (normal to the photometer optic axis) of the viewed field. In modifying this area, it is necessary to recall that the viewed field should contain no more than one drop at a time in the size range to be counted. Reference to existing data shows that one drop of diameter 1 mm and up is found on the average in one liter of air in heavy rain. Assuming a design viewed-field volume of 0.1 liter to lower the probability of two or more drops in this size range being in the field at one time, and using a beam 0.5 cm thick, a field of 200-cm^2 area could be used. This of course would place increased requirements upon the light source and its associated optics, but it would at the same time reduce the edge error. This adjustment alone would increase the volume rate of sampling by a factor of 33. Combining this alteration with an increased linear rate of sweeping the field, the volume rate of sampling may, without apparent difficulty, be increased up to 100 fold or so.

The present instrument was designed as a research tool for the study of rain in general. It appeared desirable to include smaller drop sizes, down to the order of 20 to 50-μ diameter, in such studies. The number of drops per unit volume increases rapidly in most rains as the lower size limit decreases; thus to count and size discrete drops down to this order of magnitude, the sensitive volume was kept small (6 cm^3).

Where it is desirable to observe smaller drops, the sampling rate can be maximized by making the beam as thin as possible, consistent with the drop sizes to be counted. It is probably not necessary in any case for the beam to be thicker than 0.5 cm, and for some rains it could be reduced to 0.2 or 0.3 cm. The viewing area that can be used is then determined by dividing the average space per drop of the rain field by the thickness of the beam, and by a "reducing factor" which serves to decrease the probability that more than one drop will be in the field at one time. This consideration is fundamental.

IMPROVEMENT OF AERODYNAMIC PROPERTIES

It is immediately apparent that the present source and photometer covers were not designed for minimum aerodynamic drag. There appear numerous possibilities for improving the instrument in this regard. These involve, on the one hand, arranging the source and photometer systems so that they can be housed in cylindrical or airfoil-shaped covers, and, on the other hand, the use of optical devices in such a way as to minimize the body that must be swept through the air to observe it. Specific solutions have not as yet been developed.

IMPROVEMENT OF MECHANICAL-ELECTRONIC CHARACTERISTICS

The structure of the preamplifier is moderately critical because of the likelihood that microphonic vibrations might be introduced at this point. Both the air blast used to keep the lens dry and the friction of the rotary movement tend to introduce mechanical vibrations. In addition, the impact of variable gusts of wind in field operation would doubtless have a similar effect. Much of the noise from these sources has already been eliminated by strengthening and stiffening the supports in the photometer box. Further improvement is contemplated by changing the bearings which support the main vertical shaft. In a new model an entirely different type of construction, designed to avoid these problems, would be used.

There will always be some mechanical vibration in a system such as this. The effectiveness of such vibrations for introducing microphonics can be reduced, however, by careful choice of the electronic element used in the preamplifier. The 38 tube does not have very good characteristics for holding microphonics to a minimum. We propose in future models to use a more suitable tube such as the 6788 or the CK6247, which have greatly improved rigidity.

Needless to say, the general streamlining of future models will also serve to reduce the wind-resistance- and turbulence-generated vibrations of the system.

DYNAMIC RANGE

The dynamic range depends almost entirely upon the noise level. As this is lowered by means of the improvements discussed above, it appears that a very large dynamic range can be attained. There are special problems of handling a large dynamic range because of the pulse overshoot (Fig. 11), especially when small drops follow closely after large ones. Inasmuch as the large drops are relatively rare, the error introduced by this distortion will always be small. The present amplification scheme tends to reduce this effect to a minimum. The noise level at present, primarily accountable to microphonics generated by bearing friction, is excessive, corresponding to the equivalent of a 30-μ-diameter drop. Measures are at hand for improving this situation as stated above. The dark current of the photocell and the thermal noise of the resistor represent the lowest limit to which the noise can be reduced with the present setup. This corresponds approximately to the signal from a 20-μ droplet in the field.

It therefore appears possible, with only relatively minor modifications of the instrument, to attain a dynamic range corresponding to drop sizes ranging from a minimum of less than 60-μ diameter to a large drop category ranging from 3000 μ upward. Because the signal is very nearly proportional to the square of the drop diameter (Fig. 12), this corresponds to a dynamic range of 1 to 2500.

UNIFORMITY OF ILLUMINATION AND OF RESPONSE

The optical problems encountered in a device of this sort are obviously quite complicated. In the present unit the simplest conceivable solution has been used. More elaborate systems would decrease the optical efficiency because they would necessarily increase light losses at optic surfaces. On the other hand, such elaboration would serve to provide more uniform illumination and sensitivity over the field of view. Obviously a balance of these two considerations is involved, and it is likely that the present instrument would be improved by using a two-lens arrangement in preference to the present single lens in each of the optical systems (source and photometer).

Figures 9 and 10 show, respectively, the distributions of light intensity in the beam and of photometer response to a uniform intensity, flashing light in the central plane of the beam. Some improvement of these patterns would be realized by the use of better lenses than are now in the units, but it is doubtful whether this would be appreciable unless the two-lens arrangement is adopted.

The present light source might be improved upon. No exhaustive study of available lamps has been made, and although the present source has many favorable characteristics, it is possible that a better one may be found or designed.

STABILITY OF CALIBRATION

The stability of the present instrument is primarily influenced by the aging of the light-source lamp and by the rate of draw-down of the battery voltages. Evaporation of the lamp filament and the resulting cumulative darkening of the lamp walls require that the lamp be changed at regular intervals. This, however, is a gradual process, and not too intolerable. It can be monitored quite easily by probing the beam with a standardized photometer.

The most reasonable solution of the problem of draw-down of battery voltage appears to be to use a commercially available regulated power supply. An alternative is the use of a large bank of batteries. Bulk and maintenance problems associated with the batteries tend to militate against their use.

Both the phototube and the preamplifier tube are relatively stable. When accidental breakage or aging requires that either of these be replaced, an entirely new calibration has to be made. It is also important to select carefully the particular tube that will be used in either case. The preamplifier tube should be selected for low grid current, the phototube, for uniformity of response.

DESIGN AND CONSTRUCTION OF AN IMPROVED MODEL

It is apparent from the preceding material that the photoelectric raindrop spectrometer is still in a developmental state. It is operational at present, but there are many ways in which it might be improved. Should support for further development of this instrument become available, the procedure would follow the course described below.

1. The Optical Systems

The design and construction of the optical systems and the selection of lenses should be reviewed. Since a uniformly illuminated field is required, the selection of the light source must also be considered. The characteristics of the photocell as regards uniformity of response must also enter into consideration in designing the photometer optics.

Experience with the present instrument suggests strongly that the error accountable to optical problems is probably larger than that from any other source.

2. The Physical Form

Considerations of lens-wetting and of the generation of turbulence by rotating members of the instrument have already suggested likely revisions of its form. The problems of microphonics that have arisen in the present model have served to emphasize a need for improved rigidity, particularly as regards the photometer support. These factors imply that

(1) parts that must move in the vicinity of the observed drop field should be as small as possible and should be streamlined;
(2) parts that are supported by long cantilever arms are more likely to vibrate than they would be with shorter or more rigid supports; and
(3) it may not be necessary for both the light source and the photometer unit to be exposed completely to the rain field.

Revisions of the form of the instrument have already been studied to some extent. Complete designs require more detailed investigation, possibly involving the use of mock-up models.

3. The Electronic Components

It has already been mentioned that the microphonics originating in the photometer might be reduced considerably by using a different tube in preference to the 38. Other electronic modifications, i.e., in the amplification, discrimination, and triggering components, should also receive consideration for future models. To the extent that specialized purposes may be served, the electronic systems used may be made less flexible and hence more simple.

The Counters and Readout System

No absolute criteria exist for these. As stated earlier, the present glow-counter tubes, read by photographing each minute, represent a relatively simple and inexpensive arrangement, but the data are not recorded in the most convenient form by this method. Where bulk and cost are not objectionable, a print-out system would appear to be nearly ideal. Other methods are available depending upon the uses envisioned for the data.

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