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ILLINOIS STATE WATER SURVEY
METEOROLOGIC LABORATORY
at the
University of Illinois
Urbana, Illinois

A RAINDROP CAMERA

by

Douglas M. A. Jones and Lawrence A. Dean

prepared as

RESEARCH REPORT No. 3

under
CONTRACT No. DA-36-039 SC-42446
with U. S. Army Signal Corps Engineering Laboratories
Fort Monmouth, New Jersey
Department of the Army Project: 3-99-07-022
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INTRODUCTION

This research report describes the construction of a camera for the specific purpose of measuring directly the dimensions of falling precipitation particles. The data obtained from the camera film are to be used in the determination of radar reflectivity from precipitation, and for the investigation of the cross-sectional shape of precipitation particles.

HISTORY OF DROP-SIZE MEASUREMENTS

Since the advent of radar as an instrument for detecting rainfall, interest has been renewed in the determination of raindrop-size distribution and the shape of the precipitation particles. The distribution published by Laws and Parsons (1) has been a classic in these investigations, and reference may be made to their paper for an excellent history of drop-size studies up to 1943. Since the Laws and Parsons work, additional information has been obtained by Marshall and Palmer (2) using absorbent paper and a water-soluble dye, Blanchard (3) using sooted metal screens, Boucher (4) using sugared nylon screens, Bowen (5) using a mass spectograph, and Cooper (6) using microphone impact of drops. Only a few of these investigators obtained raindrop-size samples in a rain heavier than 3 inches/hour because the gusty winds accompanying such heavy rates make the measuring techniques inadequate, or too much water is collected before the sample can be covered. The search for a solution to these two difficulties resulted in the decision to attempt photographing the drops.

In an ordinary camera the light rays which form the photographic image diverge with distance from the camera. This divergence with distance results in normal perspective; i.e. , near objects appear larger than far objects of the same size. Normal perspective introduces an inconvenience where it is desired to measure objects randomly distributed within a volume. A solution to the problem was used by Laws (7), and his basic instrument has been extended and refined for the present study.

The raindrop camera as shown in Figure 1 photographs through the long silver-colored tube extending from the power pole on the right to the left foreground. The flash equipment is housed in the shelter to the left, while the camera and associated optics are housed in the longer sectional shelter to the right. The sampling volume, outlined by the open ends of the two inverted troughs, may be seen between the two shelters. A rain sensing element to activate the equipment is located between the fence and the camera and may be seen immediately beneath the openings. An Aerovane wind set is located in a corner of the equipment area, and a weighing bucket raingage is also installed (left, behind shelter). The two timber piers at each end of the optical section of the camera support the movie camera, diagonal flat mirror, and the paraboloidal mirror independently of the plywood shelter tube, thus reducing vibration of the optical system during gusty thunderstorm winds.

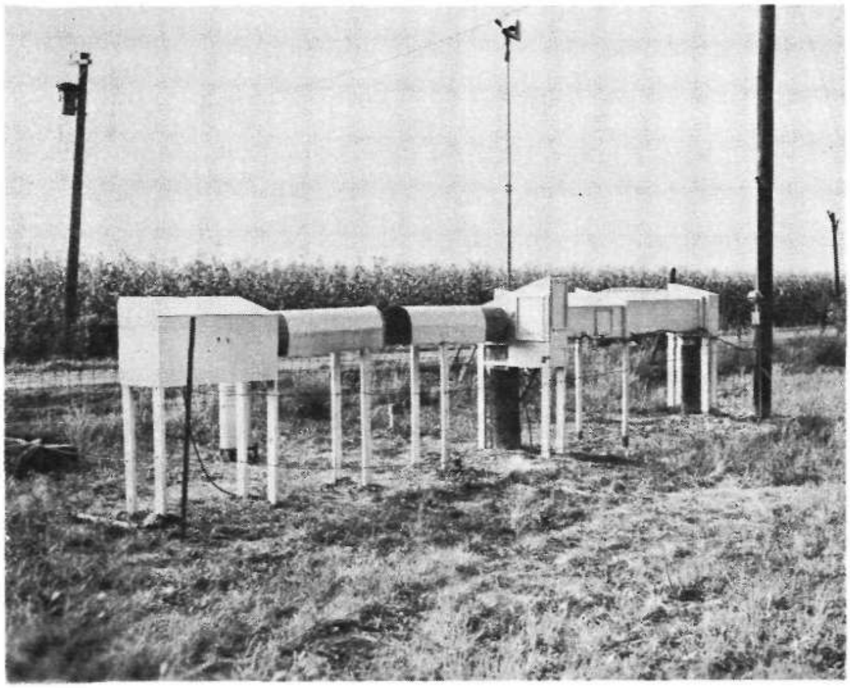


Fig. 1. The raindrop camera showing housing for mirror, flash unit, camera, and sampling volume.

COMPONENTS

The complete particle-size apparatus consists of a number of major components which are listed with their functions in the following paragraphs:

Electronic Flash Unit

The electronic flash unit was built especially to fit specifications of this study. These specifications included: light output constant from flash to flash, 10 micro-seconds effective flash duration at 24 watt-seconds energy storage, uniform illumination over a 15-inch diameter circle, and cycling time of one-third second.

The necessary energy storage was determined from a series of tests with equipment of different energy storage capacities from various manufacturers. The flash duration is short enough so that no blur from movement is detectable in the photographic image. This duration was calculated using the magnification of the optical system, the resolution of the photographic film, and the speed of fall of the largest raindrop (6. 2 mm) to be expected (8). A flash duration of approximately 20 micro-seconds was found to be the longest exposure to be tolerated. The operating voltage of the electronic equipment is 4, 000 volts, and the storage capacity for 24 watt-seconds energy is 3. 0 micro-farads. The electronic flash unit is of conventional design except for the trigger circuit. It has proven to be very reliable in operation and no variation in light intensity has been detected from flash to flash or from day to day. The schematic diagram of the electronic flash equipment is shown in Figure 2.

Telecentric Optical System

The purpose of the telecentric optical system is to normalize all particles to an equal distance from the camera lens so that direct comparison of their sizes may be made. Essentially, the telecentric optical system consists of a Newtonian-mounted astronomical telescope with the objective lens of the recording camera placed exactly at the principal focus of a first-surface paraboloidal mirror. The first-surface paraboloidal mirror must be of very high quality since each small area of the mirror's surface is of equal importance. This is evident from the fact that the camera is accepting all those rays of light which are parallel and nearly parallel before striking the surface of the mirror, and a true rendition of the particle's size is not obtained if a flaw is present in that portion of the mirror which is forming the image of the particle. Figure 3 is a diagram of the optical system.

The paraboloidal mirror used in the final instrument has a diameter of 324 mm, and a focal length of 4, 581. 5 mm. This mirror has some zonal error amounting to about one-fourth of the wavelength of sodium light in a ring about two-thirds of the radius from the center. This zonal error, which was determined using the Foucault test, was difficult to measure because of the large variations in density of the air over the 30-foot optical path of the test. A flat first-surface mirror, just large enough to intercept the converging rays of light from the paraboloidal mirror, is placed at a balance of distances so that the camera can be placed just outside the field of view of the paraboloidal mirror.

The camera optical system is so arranged that essentially only parallel rays of light in the object space are accepted on the film. Because the camera accepts only parallel rays of light, the concave mirror surface must be paraboloidal in order to cause the bundle of light rays to meet in a point at a principal plane of the camera objective lens. However, since the 324-mm diameter mirror in the camera has a focal length 14. 1 times its diameter, the difference between a spheroidal and paraboloidal surface is negligible,

Camera

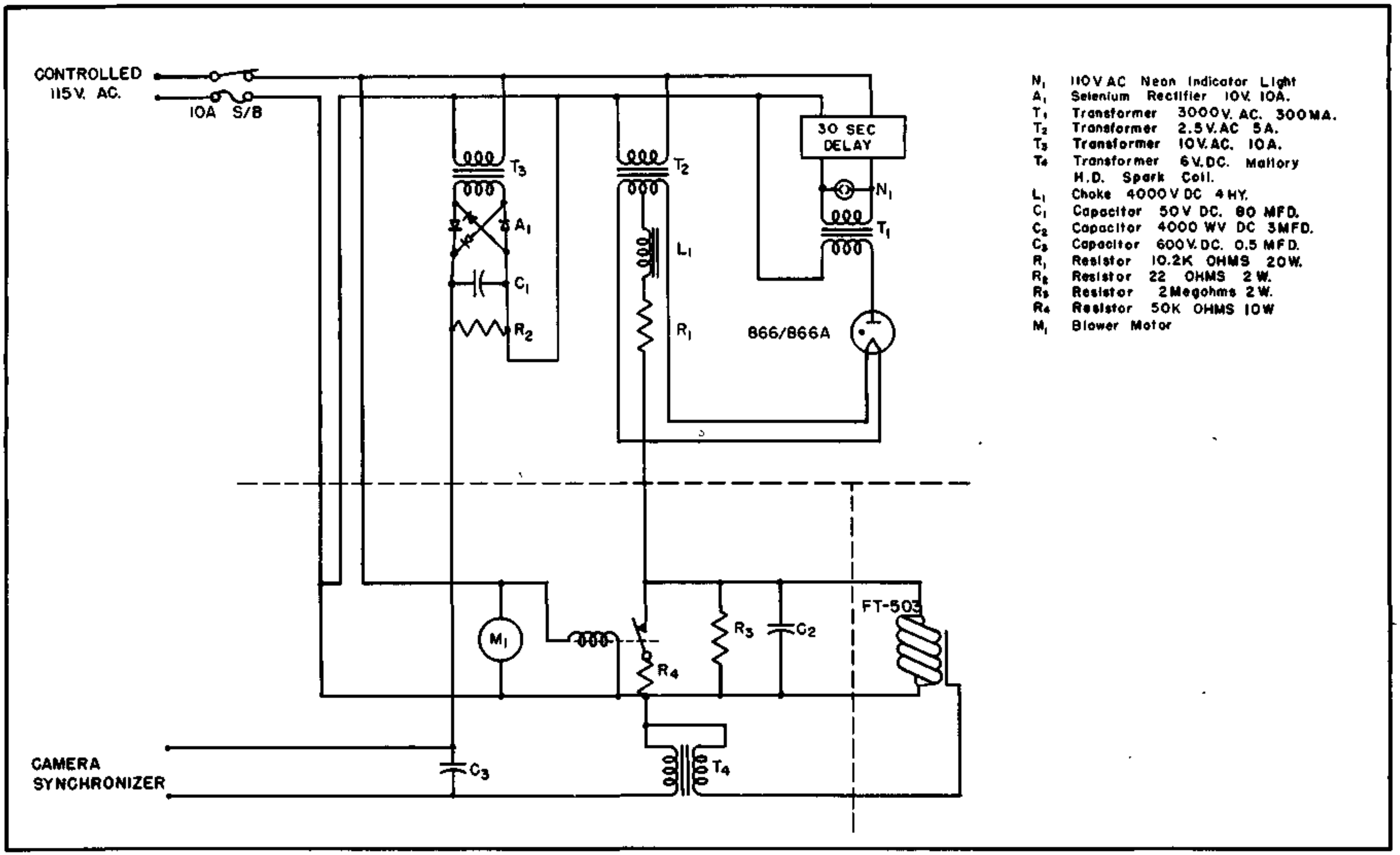
The camera used with the particle-size apparatus is a modified PH-330-K 35-mm motion picture camera. This camera was not designed to prevent all light from leaking around the shutter when the camera mechanism is not actuated. In fact, there is no device included in the camera which acts as a positive stop to insure that the shutter always stops in front of the film. Thus, it was necessary to modify the camera in such a way that a negligible amount of light strikes the film during those intervals when the camera shutter is closed. It was found necessary to insert sheets of black paper at certain points in order to reduce the amount of light leaking around the closed shutter.

A lens barrel was made to fit a Bausch and Lomb Tessar Series 1C f/4.5 210-mm focus lens. The 210-mm focal length was selected in order that the magnification of the system would cause the resultant image on the film to be the exact size of the smallest dimension of the film; thereby, using the available film area most efficiently. Since a 35-mm movie frame is 16 mm x 24 mm and the particles are recorded on an area only 16 mm x 16 mm, there is an area 16 mm x 8 mm available for the simultaneous recording of date and time of the exposure. Inserted in the right-hand side of the lens barrel, as viewed from the rear of the camera, is a supplementary barrel for the identification lens. A right angle prism extending into the objective lens barrel places the image of the identification information on the film area provided. Figure 7 is a photograph showing the location of the various items. No aperture has been included in the identification lens system, and the correct exposure is obtained by varying the amount of light from an incandescent lamp.

The camera has been fitted with a single-frame device. This device is operated by a continuously running motor which is coupled to the camera through a suitable gear train and clutch for exactly one-half turn of the camera shutter mechanism. The camera shutter is comprised of two sections so that one-half turn of the shutter will aways result in the exposure of one film frame. Shutter rotation is constant and non-variable. Incorporated in the single-frame device is a cam and microswitch arrangement which synchronizes the firing of the electronic flash unit with the exposure of the single frame. The camera uses 100-foot, 200-foot or 400-foot reels of film.

Timing Devices

An attempt has been made to make the operation of the particle camera as automatic as possible and to construct it so that it starts operating as soon after the beginning of a rain as possible. This is done so that a complete history of drop-size variations in a particular rain may be recorded. This has been accomplished by controlling the electrical supply to the camera through a series



N_1	110V AC Neon Indicator Light
A_1	Selenium Rectifier 10V. 10A.
T_1	Transformer 3000V. AC. 300MA.
T_2	Transformer 2.5V.AC 5A.
T_3	Transformer 10V.AC. 10A.
T_4	Transformer 6V.DC. Mallory H.D. Spark Coil.
L_1	Choke 4000V DC 4HY.
C_1	Capacitor 50V DC. 80 MFD.
C_2	Capacitor 4000 WV DC 3MFD.
C_3	Capacitor 600V.DC. 0.5 MFD.
R_1	Resistor 10.2K OHMS 20W.
R_2	Resistor 22 OHMS 2W.
R_3	Resistor 2Megohms 2W.
R_4	Resistor 50K OHMS 10W
M_1	Blower Motor

FIG.2 ELECTRONIC FLASH SCHEMATIC

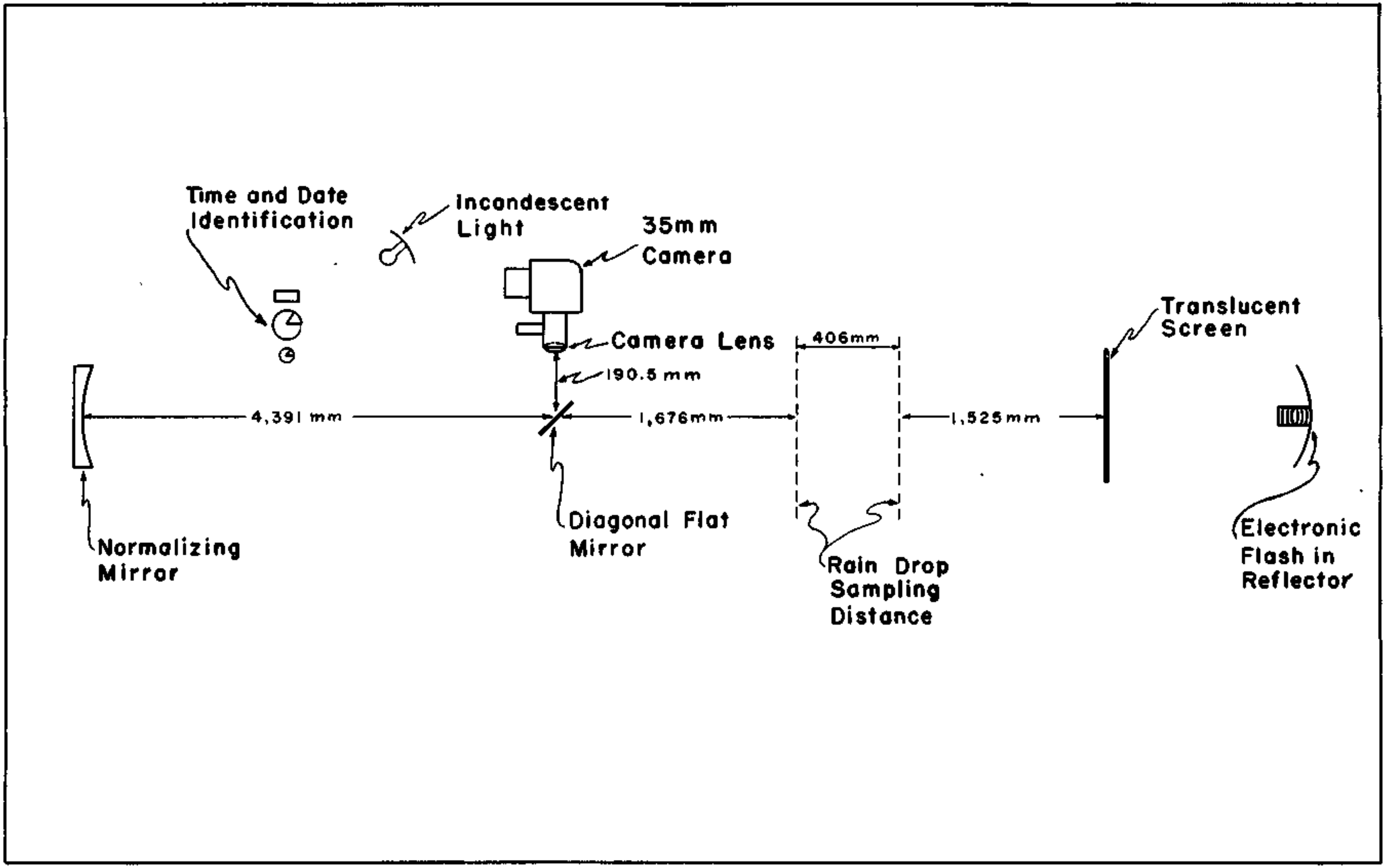


FIG. 3 OPTICAL SYSTEM (NOT TO SCALE)

of relays and timers which control the interval of time elapsing between successive exposures, the warm-up of the equipment, and the shut-down of the equipment.

A rain-sensing element has been built so that the camera may be operated unattended. This consists of a brass screen mounted above a brass plate about four and one-half inches square and separated from the plate by a thin sheet of glass cloth. Heat is supplied to the brass plate by a thermostatically-controlled heater. Whenever rain is occurring, the sensing element is maintained at a temperature such that water standing on the plate evaporates rapidly.

This plate, insulator, and screen form a switch in a 150-volt DC circuit which controls the coil of a plate relay. Laboratory experiments indicated that all but the smallest drops resolved by the camera decrease the resistance across the switch sufficiently to close the relay. Further tests indicated that after the element has reached operating temperature, a single drop is evaporated in approximately six seconds, and that the element, after being completely soaked, dries sufficiently to open the relay after about five minutes.

The plate relay is incorporated into the circuits shown in Figure 4 to control the power to the flash equipment, camera drive motor, data illumination, and timing motors. Shorting of the rain switch results in immediate delivery of power to all of this equipment. A 30-second delay is incorporated into the flash equipment to allow the 866/866-A rectifier tube to warm-up. The purpose of the additional relays and delay timer on the control chassis is to prevent the rapid switching of the plate relay during light rainfall from affecting the operation of the camera. The control chassis is provided with a switch for operating the camera independently of the rain-sensing element.

Two timing motors are used to obtain pulses which trigger the camera. Continuous pulses at intervals of one-third second, or a series of 36 pulses at intervals of one-third second repeated each minute, are available. The series of 36 pictures at minute intervals was chosen to gather a large amount of data throughout a storm, and was considered an upper limit of sampling rate because of the large amount of film used.

The interval of one-third second for individual photographs was chosen also so that the smallest drop which could be resolved and measured would have time to fall out of the sampling volume before another picture was taken. The diameter of the large mirror which determines the maximum vertical dimension of the sampling volume is 324 mm, and the fall velocity of a 0. 25 mm drop as given by Gunn and Kinzer (8) is approximately 92 cm $\sec^{-1}$. Using this criterion, a photograph interval of one-third second was chosen.

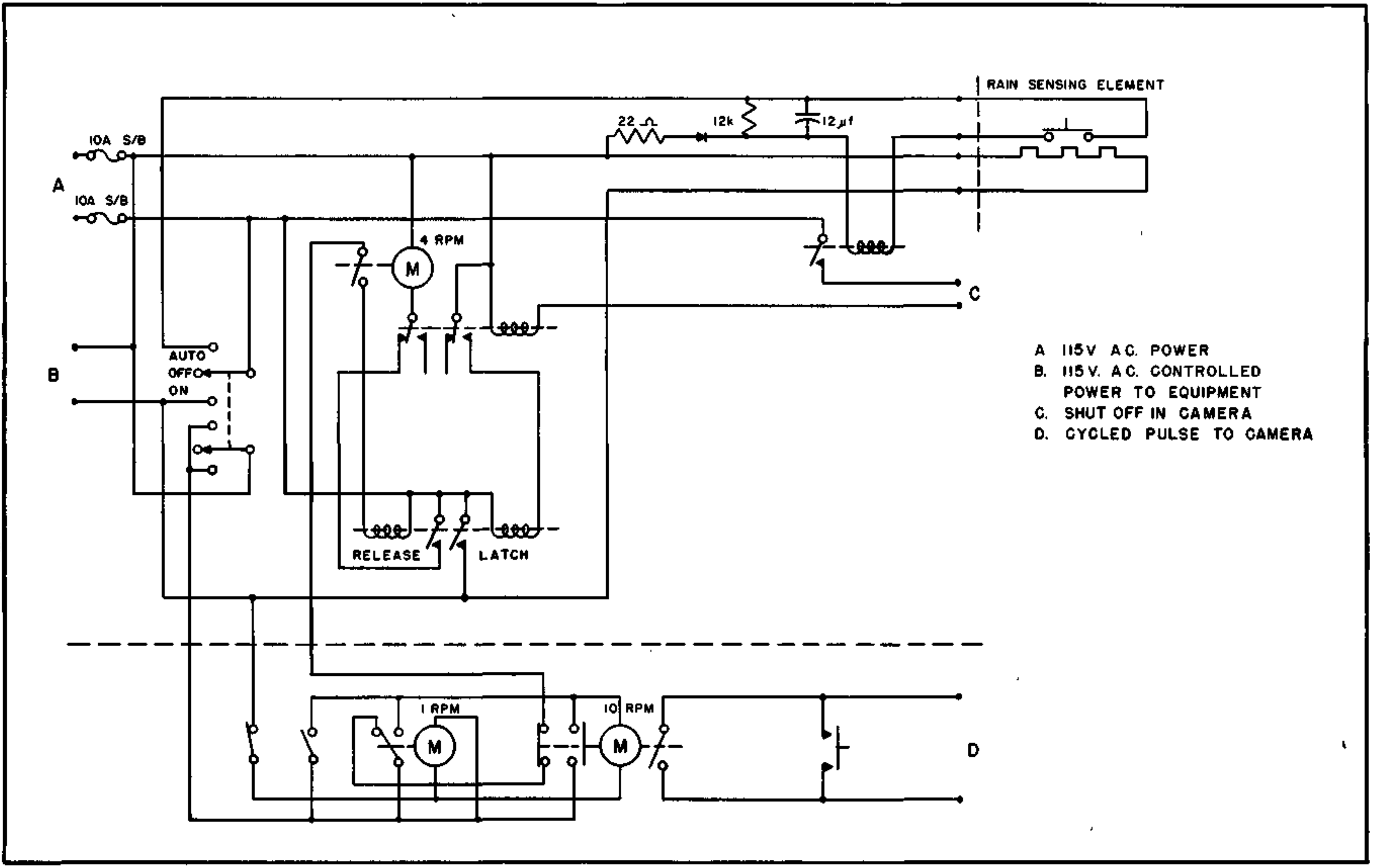


FIG. 4 CONTROL AND TIMING CHASSIS

MEASUREMENT ACCURACY

A knowledge of the precision of any measurement system is of prime importance. For an optical system recording on photographic film, several factors limit the degree to which images may be resolved. These are: (1) the combined aberrations and distortions of the lens system, (2) the resolving power of the photographic film, (3) the disc of diffraction resulting from the aperture stops in the system, and (4) the circle of confusion arising from objects not being in the actual focal plane of the optical system. The sampling volume of the camera and, therefore, the number of raindrops appearing on a single negative is limited by the maximum allowable size permitted ,the circle of confusion.

The aberrations and distortions of the lens system cannot be treated quantitatively. However, the system can be tested by means of a resolution card. To satisfy an assumption to be stated later, the resolution possible with the optical system must be better than the desired resolution as limited by the other effects. An original system, assembled and tested using the relative aperture dictated by preceeding factors (3) and (4), was found to limit appreciably the quality of the image. Therefore, the original objective lens used on the camera, an achromat, was replaced with a Bausch and Lomb Tessar as previously described. Repeated tests indicated that the system satisfied the requirement that optical system limitations be less than those limitations imposed by factors (3) and (4).

The resolving power of a photographic emulsion is sometimes given by photographic film manufacturers in terms of the number of lines per millimeter which may be resolved on the film; however, since rating of the resolving power is extremely subjective, it was thought desirable to test several films in the precise conditions under which they were to be used. Again, the resolving power of the film employed must be better than that desired, considering factors (3) and (4). Films tested included Eastman Microfile, Eastman Background-X, Eastman Plus-X and Super-XX, Ansco Supreme, and DuPont Microcopy and Superior I. The copy films, such as Microfile and Microcopy, were found to require more exposure than was obtainable from the electronic flash equipment at the capacitance used. More light is obtained by increasing capacitance which increases the charging time of the equipment and drives the flash tube harder. Eastman Plus-X and Background-X Professional Films and DuPont Superior I were tested extensively, and these films were found to have a resolving power better than that necessary to satisfy the requirements. Eastman Background-X was chosen for use because of the relatively high contrast it affords and its resistance to scratching. If exposure and development are correct within very narrow limits, Background-X is capable of a resolying power of 112 lines per millimeter in the film plane, which corresponds to an ability to distinguish two objects 0.194 mm apart in the object space.

Diffraction and the circle of confusion must be considered together and a compromise reached between their limitations as they affect resolution. This may be treated mathematically.

Let us consider any optical system which forms an image and describe it in terms of the principle planes, focal points, and the entrance and exit pupils. Further assume Rayleigh's criterion for resolution; i.e. , the distance between the centers of the diffraction patterns must be equal to the radius of the first dark ring.

Following the nomenclature of Hardy and Perrin (9):

H and H' are the principal planes,
E and E' are the entrance and exit pupils respectively,
p and *p'* are the radii of the pupils E and E' respectively,
F and F' are the focal points,
P_O and P'_O are the distances of the focal points from the corresponding pupils, and
P and P' are the distances of the object and image from the corresponding pupils.

In Figure 5 the half angle, 9, of the disc of diffraction is given by the expression

$$\sin\theta = \frac{0.61\lambda}{\rho'} = \frac{z'}{P'}, \tag{1}$$

$$\text{or } \rho' = \frac{0.61\lambda P'}{z'} \tag{2}$$

Here z' is the radius of the disc of diffraction in the image space, and is the appropriate wavelength of light.

The magnification of the system can be expressed by the formula

$$m = \frac{z'}{z_1} = \frac{\rho P'}{\rho' P}, \tag{3}$$

where z_1 is the radius of the disc of diffraction in the object space. Elimination of z' between equations (2) and (3) yields the formula

$$\frac{P}{\rho} = \frac{z_1}{0.61\lambda} \tag{4}$$

The limitations due to the circle of confusion arising from depth-of-field considerations (Figure 6) may be expressed in terms of the above quantities by the formula

$$d = d_1 + d_2 = z_2 P \left(\frac{1}{\rho - z_2} + \frac{1}{\rho + z_2}\right) \tag{5}$$

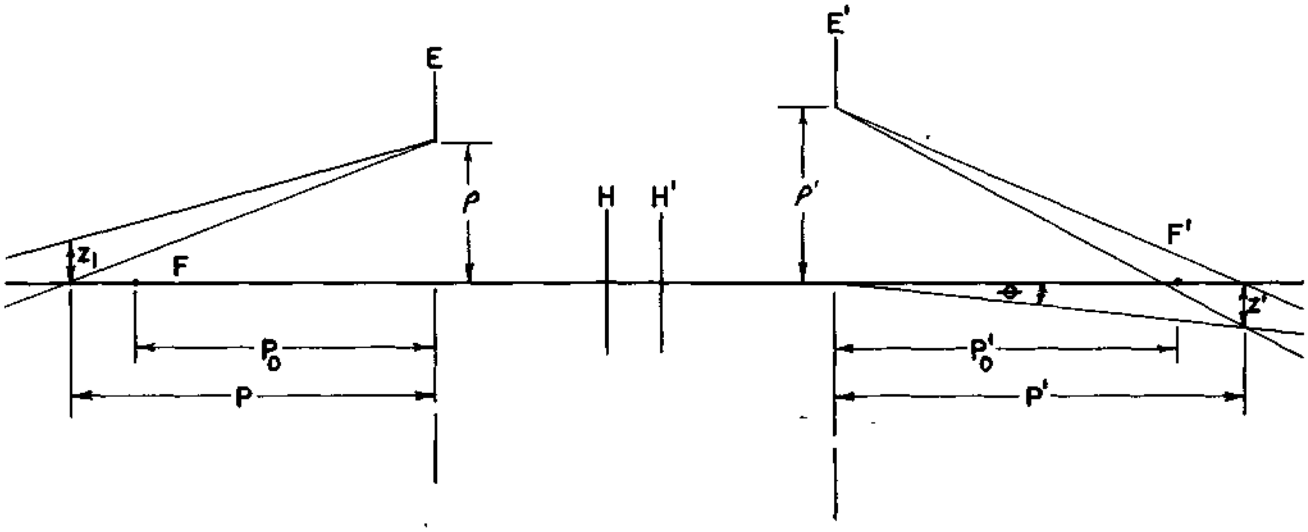


FIG. 5 GENERALIZED OPTICAL SYSTEM ILLUSTRATING DIFFRACTION

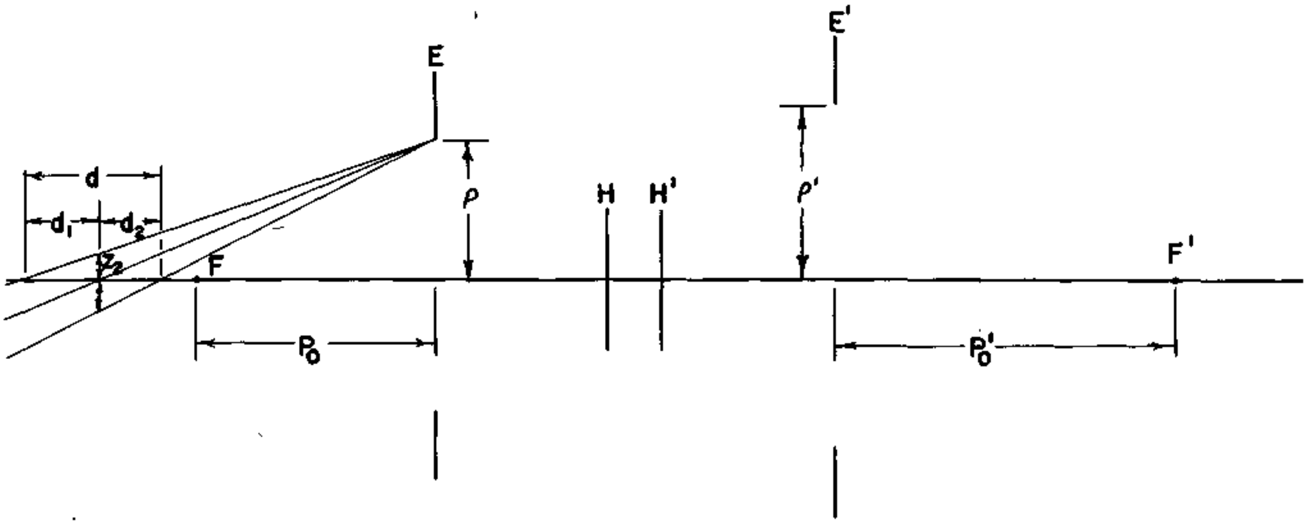


FIG. 6 GENERALIZED OPTICAL SYSTEM ILLUSTRATING DEPTH-OF-FIELD

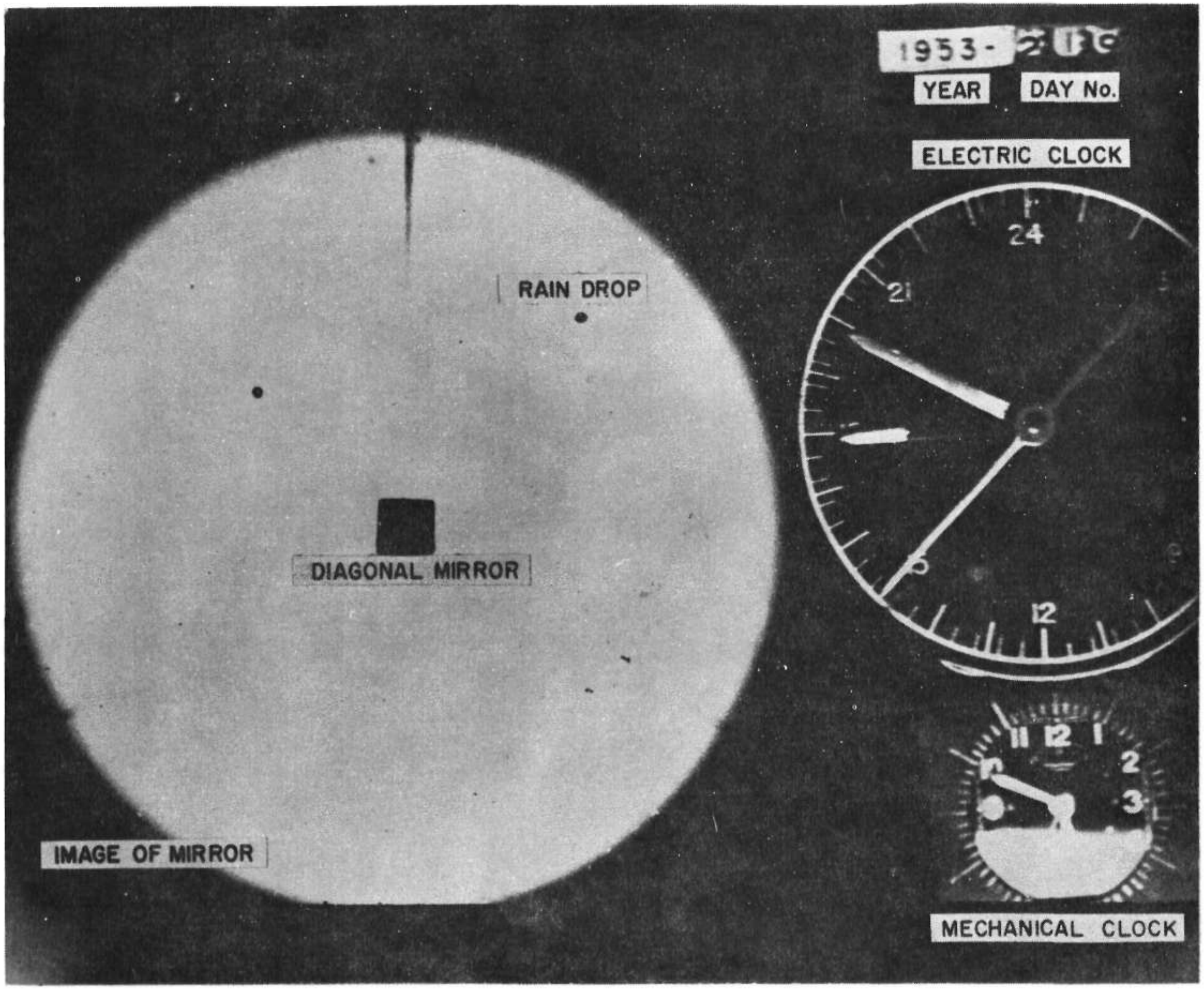


Fig. 7 Interpretation of Raindrop Photograph.

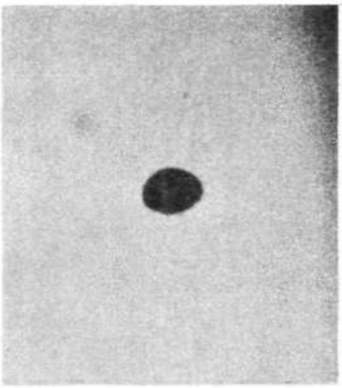


Fig. 8. Largest Raindrop Photographed.

Fig. 9. A Shattered Raindrop.

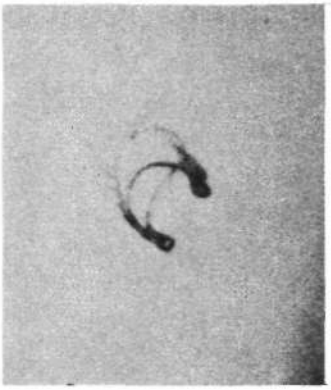
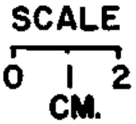


Fig. 10. A Bagging Raindrop.



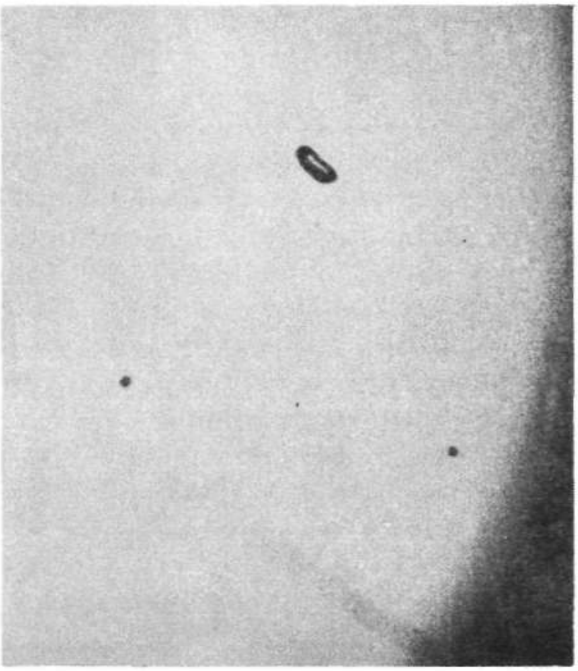


Fig. 11. A Non-Symetrical Vibrating Raindrop.

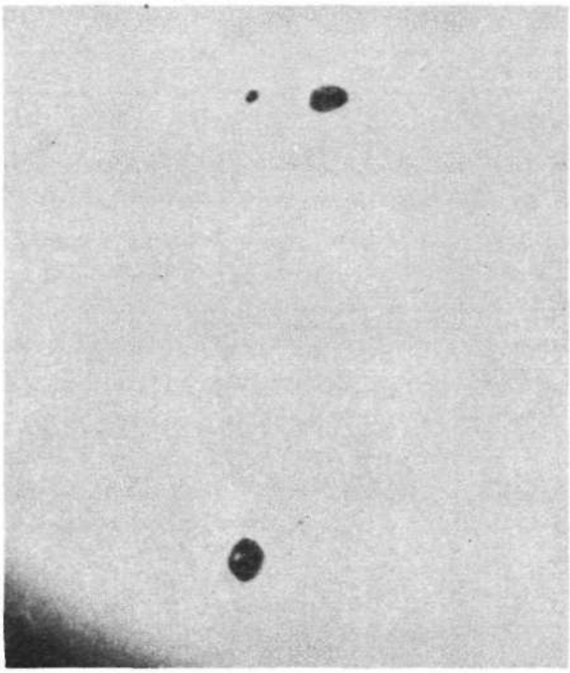


Fig. 12. Three Raindrops at Three Different Angles.

where z_2 is the radius of the circle of confusion in the object space, d is the total depth-of-field corresponding to any value of z_1, and d_1 and d_2 are the distances of the given depth of field on either side of the focal plane. Since z_2 is small compared with ρ, this may be written

$$d = \frac{2z_2P}{\rho} \quad . \tag{6}$$

For a more complete discussion of diffraction and depth-of-field effects see Hardy and Perrin (9) or other standard texts.

Inspection of formulae (4) and (6) indicates that both z_1 and z_2 depend upon ρ and P, and that, in turn, the depth-of-field, d, depends upon the choice of these quantities. Since the possible sampling volume of each photograph depends upon d, it is desirable to make d as large as possible. Furthermore, the quantities z_1 and z_2 must be small to provide good images. When d is large and z_2 is small, it can be seen from formula (6) that the ratio $\frac{P}{\rho}$ must be large. Since it is desirable that neither z_1 or z_2 exceed the other, z_1 may be equated to z , and the quanti $\frac{P}{\rho}$ iminated between (4) and (6) to yield

$$d = \frac{2z^2}{0.61\lambda} \tag{7}$$

where z represents either z_1 or z_2.

From this equation it can be seen that, if the resolution is limited equally by diffraction and lack of depth-of-field, aberrations of the lens system being unimportant, then the constants of the optical system have no effect on the depth-of-field. Therefore, no alteration of the focal lengths of the mirror or camera objective will increase the depth-of-field and the use of a telecentric system, such as the one previously described, imposes no limitations other than those which would be experienced with any optical system.

For the purpose of photographing raindrop shape, circle of confusion and disc of diffraction diameters of 0. 25 mm in the object space were used. Several factors dictated this choice: (1) the resolution of the film limits definition of images to 0. 2 mm, (2) resolution should be as good as possible to permit measurement of particles within very varrow limits, (3) deviation of raindrop shape from spherical should be detectable to 0.25 mm, since a difference of 0. 25 mm between the lengths of the major and minor axes of a 2. 5 mm drop results in an axial ratio of 0. 9 (10).

Since the depth-of-field is decreased as the resolution is made more critical, the maximum tolerable value of z is desirable. Several numerical examples may serve to illustrate this. Using an approximate value of 5×10^{-4} mm for λ , equation (7) yields the following results: for resolution of 0. 5 mm in the object space ($z = 0.25$ mm) the depth-of-field is 16. 1 inches; a depth-of-field of 4.04 inches is possible with a resolution of 0.25 mm; and for a resolution of 0. 2 mm the depth-of-field is only 2. 54 inches.

Two of the above combinations have been used to collect data. For the purpose of raindrop shape studies, where critical definition of the drops is more important than the total number of drops obtained, 0. 25-mm resolution, 4. 04-inch depth-of-field, and from equation (4), a relative aperture of f/11 were used. Resolution tests substantiated the fact that 0. 25-mm resolution was obtainable through four inches. Since the amount of natural light cannot be decreased, a neutral density filter must be used to limit the amount of light entering the camera at this larger lens opening.

For the purpose of determining the drop-size distribution, a larger sample, and thus a larger sampling volume, is desirable. Accordingly, a resolving power of 0. 5 mm obtainable through 16-in. or 406-mm depth-of-field was chosen. 'Each photograph represents a sample through 0. 033 m^3, and if the 36 photographs obtained in 12 consecutive seconds are combined as a sample, the volume is 1. 198 m^3 in which an average of 200 drops are photographed. Tests with a lens aperture of f/18. 0 have shown that drops 0. 5-mm and larger are observed and a resolution of 0. 3 mm is obtained through the 406 mm. The figure of 0. 3 mm is used as the median of the class interval in drop size tabulation.

RESULTS

Several photographs obtained with the drop camera are included as examples. In general, these illustrations are not examples of the average photograph obtained, since the raindrop images on an average photograph are too sparse or too small to show up well in a reproduction. Instead, those photographs which illustrate the unusual data obtainable with the camera are shown.

Figure 7 is an interpretation of the raindrop photographs and is self- explanatory.

Figure 8 shows the largest drop yet obtained with the drop camera. The photograph was obtained 7 August 1953 during a heavy shower accompanied by small hail. The drop measured, 10. 4 mm x 7. 6 mm. It is conceivable that the drop is hail and not water, since theoretically it is larger than a water drop may grow.

Figure 9 illustrates one of several cases in which a number of relatively small droplets appear in close proximity, suggesting the possibility that the group originated from a large unstable drop a moment before. A rain drop measuring 4. 8 mm x 4. 0 mm appears above the cluster of small drops, not shown in this portion of the photograph.

Figure 10 shows a phenomenon which is thought to be the first instance of "bagging" observed in nature. Such a phenomenon has been observed in studies of drop break-up in the laboratory, and an equation has been derived to explain the conditions existing at the moment of break-up (13). Although the cluster of droplets in Figure 9 appear in approximately the correct position to make it seem that they are the result of the "bag" in Figure 10, actually the "bag" of Figure 10 was photographed 3 seconds after the droplets in Figure 9 were photographed. However, it is believed that the droplets found in Figure 9 are the result of the break-up of a "bagging" raindrop.

Using the data obtained from Figure 10 a calculation based on the equation $(u-v)^2d = 612$ given by Lane (11), where u is the critical velocity of the air stream in m sec^{-1}, v is the velocity of the entrained drop at the instant of breaking in m sec^{-1}, and d is the equivalent spherical diameter in millimeters shows that there was an easterly wind blowing downward at 35° from the horizontal at 7 m sec^{-1}. The assumption for the mass of water contained in the rim of the "bag" as given by Lane was used.

Attention is now directed to another phenomenon for whose observation the drop camera has shown itself to be useful. It has been observed that those larger water drops, which are non-spherical and tend to flatten due to aerodynamic pressures, do not always remain with their flattened sides toward the ground. It would be expected that the major axis of the rain drop cross-section would be so oriented as to balance the aerodynamic and gravitational forces acting upon the drop. Evidently, the forces are not those simple ones which would be first assumed, i. e. , a steady horizontal wind. Figure 11 and 12 illustrate the slope of the major axis with the horizontal, with Figure 12 showing three drops each with a different axis orientation.

Another fact which may be determined from raindrop photographs is the lack of consistency of the axial ratio of raindrops with equal major axis length; i. e. , one drop may measure 5 mm horizontally and 4 mm vertically, thus having an axial ratio of 0. 8; while another drop may measure 5 mm horizontally, but only 3 mm vertically - an axial ratio of 0. 6. The drop shown in Figure 10 measures 8. 3 mm along the major axis and has an axial ratio of 0. 45. This lack of consistency in drops of equivalent spherical diameter or equal major axes may be explained by the phenomenon described by Blanchard (12). He noted that there were two types of oscillations which cause the axial ratio to change with time; a rotational oscillation about the vertical axis and a vibrational oscillation.

CONCLUSIONS

It has been shown that the drop camera is capable of obtaining the data for which it was designed, that of the rain drop-size distribution. It is capable of resolving drops larger than 0. 5 mm to an accuracy of 0. 3 mm, and it samples a volume of space large enough so that an average of 200 or more drops per sample (36 exposures) are obtained.

Over and above the basic information of the drop-size distribution, the camera will record the cross-sectional shape of the particles photographed and their axial orientation. The camera also has photographed some unexpected drop configurations thought to represent a phenomenon of drop break-up.

Within certain limits the drop camera is quite adaptable to the type of data that might be required for precipitation particle investigations. These limits are: (1) the limitations imposed upon the depth-of-field by the required resolution, (2) the speed of the particle and the flash duration required to prevent appreciable blurring of the image, and (3) distortion of non-rigid particles by turbulence about the sampling opening.

SUGGESTIONS FOR FUTURE WORK

It is thought that much information would be obtained from an ordinary camera and light source photographing at right angles to the drop camera. The light source could be another FT-503 flash tube on an extension cord from the present power pack.

Another informative use for the drop camera would be anarrangement allowing more than one image of the same rain drop to be photographed, either on the same negative or on separate negatives. Multiple exposure on the same negative would probably be the method most quickly obtained. The present equipment would be capable of modification for either method. If particles moving considerably faster than 10 m/s are photographed or if a magnification greater than 1:1/10 is to be used, the flash duration would have to be shortened accordingly.

A recent paper by McDonald (13), describing the forces acting upon a water drop, noted the lack of suitable photographs of falling water drops and particularly falling raindrops. It would seem that the drop camera would be an ideal instrument for recording the data for the study of forces determining drop shape. For shape studies it is not necessary to limit the volume photographed strictly, since blurring of out-of-focus images will eliminate them. It would not be necessary to have limiting shields near the volume photographed; therefore, turbulence distortion should become negligible.

As pointed out in the discussion of measurement accuracy, resolution increases and the depth-of-field decreases as the aperture size is increased; by sacrificing the number of drops which are to be measured by increasing the size of the aperture, an accuracy of measurement limited, only by the resolution of the photographic film may be achieved. Greater measurement accuracy may be attained if a larger magnification ratio is used; i. e. , when a camera lens with focal length longer than 210 mm is used on the present camera. To increase the magnification without increasing the film size would mean a further reduction in number of drops sampled. A practical limit of accuracy will be reached as a quality lens of long focal length and large aperture becomes too expensive. Of course, smaller droplets become detectable and measurable as measurement accuracy increases.

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