Final Report

AGGLOMERATION OF CLOUD PARTICLES AND PROJECT HI-CUE PARTICIPATION

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ABSTRACT

The several components necessary to conduct experimental observations of the coalescence of cloud droplets under the influence of an introduced vortex have been developed. These components include a laboratory cloud box (vertical low-speed tunnel), a vortex-generating mechanism consisting of an airfoil and a propulsion device, and a telemicro camera capable of 5x magnification of objects 8 in. from the camera objective.

Analysis of the effects of a model vortex upon a population of drops has been done by means of electronic analog techniques, and these support the hypothesis that a single vortex tends to cause drops to become concentrated in a concentric band. The likelihood of collisions is thus increased.

Radar studies of chaff drops in Project Hi-Cue, 1959, show that in one isolated case, a circulation somewhat like that postulated by Newton and Newton did occur. Further experiments along these line are recommended.

Data collected at Flagstaff under Project Hi-Cue, 1961, are currently under analysis. The data logs for the raindrop-size spectrometer, the theodolite pibals, and the AFQ-40 radar are included. In addition the results of basic computations on the raindrop-size and the pibals are reported.
INTRODUCTION

The experimental study of the role of turbulence in the generation of rain-sized drops in clouds was continued under the present contract from the stage of development reported previously. Briefly summarized, the problem had been approached in terms of the needs (1) to generate reproducible clouds of water droplets in a space large enough so that known "turbulence" could be introduced and its effects upon the cloud evaluated, (2) to generate reproducible "turbulence" in the artificial clouds in a manner so as to avoid any extraneous disturbances of the population of cloud droplets, and (3) to develop the means to observe and evaluate both the initial clouds and the effects upon them of the "turbulence."

The earlier report covers the developmental phases for needs (1) and (2). Refinements have been made under the present contract (Chapter 1). The third requirement was attacked mainly under the present program (Chapter 2). An analysis of the process envisioned, that is to say, of the droplet motions resulting from the action of a vortex upon a population of cloud droplets, has been done using electronic analog computing methods (Chapter 3). The extensive developmental work required was seriously hampered by necessary limitations upon funds, and was further curtailed by the diversion of some funds to collaborative efforts under Project Hi-Cue. The first of these collaborative field studies was undertaken in Summer, 1959, and is reported briefly in Ref. 1. Analysis of the field data obtained under this program was continued under the present contract (Chapter 4). Finally, the collaboration under Project Hi-Cue was increased to include both radar and raindrop-size spectrometry in Summer, 1961 (Chapter 5). The results of this field program are being analyzed together with data collected by other project participants.
CHAPTER 1

REFINEMENTS AND MODIFICATIONS OF THE CLOUD: EXPERIMENTAL FACILITIES

1.1 THE FLOW SYSTEM

To obtain a fine adjustment of the air pressure, and to provide a safety device for the system, an adjustable pressure regulator has been installed. This will prevent pressure build-up in the system in the event of stoppage in the water filter or the cooling coils.

A Wilkerson model 5700-3 air filter was installed to filter oil from the compressed air stream.

The water trap was reduced in size somewhat on the basis of experience. It should suffice for continuous operations up to about 6 hours in duration.

The rate of flow of air into the mixing chamber, and thence into the cloud chamber is measured by means of a pitot-tube and draft-gauge arrangement. The relation of the draft-gauge reading to flow of air in the chamber depends upon the temperatures of the input air and of the chamber as well as the respective cross-sectional areas. Using the built-in values of the cross-sectional areas, the vertical velocity in the chamber is

\[ U_c = 0.0483 \frac{\tau}{\sqrt{T_1}} \sqrt{P} \]

where \( T \) is the temperature in the chamber, \( T_1 \) is the input air temperature (both in °K), and \( P \) is the velocity pressure as indicated by the draft-gauge in inches of alcohol.

Equating this expression to the Stokes' Law terminal velocity expression allows solution for the diameter of droplets that will be just supported by the upward air flow:

\[ d_{cm} = \frac{869 \mu T}{\rho_w g} \]

where \( \mu \) is the viscosity coefficient of the air, \( \rho_w \) is the density of liquid water, \( g \) is the gravitational acceleration. An order of magnitude approximation reduces this expression to
\[ d_{\text{microns}} \approx 18 (P)^{1/4} \]

1.2 VELOCITY PROFILE MEASUREMENT

To evaluate the chamber design, suitable documentation of the vertical velocity profile throughout the chamber appears to be appropriate. Furthermore, as indicated above, a complete knowledge of the vertical velocities in the chamber would be useful in determining the drop-size spectra and their changes. Accordingly, attention has been given to the problem of vertical velocity measurement in the chamber.

Because the velocities are very low, of the order of 1.2 to 1.5 cm per sec, special techniques of measurement are required. Most study has been applied to the falling sphere method. The method involves a comparison between free-fall velocities of a sphere in still air and those observed in the upward current of the cloud chamber. An ideal sphere for the purpose is one large enough to be photographed readily having a free-fall speed of 10-12 cm per sec. Changes of the order of 10 percent of this rate should then be readily detectible.

A ping-pong ball has good photographic characteristics, but its terminal fall speed is about 870 cm per sec. Thus it accelerates through its entire trajectory when dropped from the upper part of the chamber, and its use in this way to make precise air flow measurements is not promising.

Soap bubbles and bubbles of thin plastic may be blown in the chamber and released. The fall speeds of these, for radius about 5 cm, are in the vicinity of 5 cm per sec. Neither plastic nor soap bubbles are readily reproducible, however. Further, the fragility of the soap film, and the non-sphericity of the plastic bubbles complicates their use. The tendency for the bubbles to acquire a rotary motion at the time of release, and of the soap bubbles to retain a variable-sized drop of water also complicates the interpretation of their fall speeds. For a spherical bubble falling at terminal velocity with respect to the air stream, the equation of motion reduces to

\[ U^2 = \frac{2gV(T_b)}{C_D \rho_a(T_a) A(T_b)} [\rho_b(T_b) - \rho_a(T_a)] \]

where \( U \) is the terminal velocity of fall of the bubble, \( V \) is the bubble volume, dependent upon the bubble temperature, \( T_b \); \( C_D \) is the drag coefficient and \( A \) is the cross-sectional area of the bubble; the density of the bubble (and contained air) and of the environmental air are given by \( \rho_b \) and \( \rho_a \), respectively. Experimentally, the problem of the thermal lag of the bubble appears to be quite important. In falling through the impressed temperature inversion in the cloud chamber, the bubble has been observed to come to a gradual stop and then slowly
resume its downward motion. This effect is attributed to thermal lag.

Microballoons, which are phenolic bubbles of sizes ranging from 10 to 100 microns diameter, are available from the Union Carbide Plastics Company. Their usual purpose has been to reduce evaporative losses from bulk reservoirs of volatile fluids by covering the surface of the fluid. Their Stokes density is below 0.3 gm/cm³, and their terminal fall speeds are of the right magnitude for the present purpose. Photographically, however, they are difficult to use because of their small size and pale purple color. In short, a photographic method that could record the fall of Microballoons, could record that of water droplets of comparable size more readily.

In tests of the ping-pong ball as a means of measuring the air speed in the chamber, a possibility other than just dropping the ball into the chamber was brought out. The ball bounced in such a way that the apex of its flight could be photographed, and it became apparent that its upward and downward velocities at and near the apex of an upward-projected trajectory might indicate quite accurately the rate of upward drift of the air stream. Because the drag force acts with gravity on the upward branch and opposes gravity on the downward branch of the flight, and because the Reynolds number for the ball is about 20v, where v is the velocity of the ball with respect to the air stream, the motion is mainly in the region of rapidly changing drag force between the Stokes' region (Re < 0.1) and the constant drag region (10^3 < Re < 2.5 x 10^5). Our interest is focussed upon the lower values of Re up to about 200, but the problem is not readily solved by direct mathematical analysis, primarily because of the non-linear variation of the drag coefficient, C_d.

1.3 THE AIRFOIL, CARRIAGE, AND ACCELERATION SYSTEM

All components of the airfoil and carriage system were modified. The original airfoil had become broken in the course of earlier experiments, and a new design was developed in the light of experience gained with the apparatus. To minimize the special effects generated at the tips of the airfoil, the new model was made longer. The chord dimension was also increased to produce a somewhat larger vortex. The new airfoil is NACA type 634-021, and has a span of 10 in., a chord of 6 in., and an aspect ratio of 3-1/3.

A new carriage and suspension system was developed to carry the increased load and to reduce the effects of transient vibrations in the system. The new system employs a single load-bearing track upon which two wheels of the carriage run, and an overhead track upon which two more wheels run to maintain lateral stability. The carriage wheels are 1-in.-diameter nylon pulleys. The airfoil is cantilevered from this carriage into the central section of the chamber.

The new arrangement provides a distance of 4-1/2 in. from the airfoil tip to the section of the cloud and vortex that is recorded by the telemicro-camera. This provision makes negligible the propagation of end effects into the test region.
For the accelerating system, a garage door spring was selected. The virtue of the long, low spring-constant unit is that the accelerating force can be maintained relatively constant over the entire acceleration distance.

It was decided that the airfoil should be brought to maximum velocity in the distance of one chord-length (6 in.), and the suspension is so arranged that a wide range of acceleration forces may be applied. Pertinent data are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of carriage</td>
<td>10.5 oz</td>
</tr>
<tr>
<td>Weight of release mechanism</td>
<td>5.0 oz</td>
</tr>
<tr>
<td>Weight of spring</td>
<td>1 lb 0 oz</td>
</tr>
<tr>
<td>Unextended length of spring</td>
<td>14 in.</td>
</tr>
<tr>
<td>Spring constant</td>
<td>1.33 lb in. (^{-1})</td>
</tr>
<tr>
<td>Spring tension at zero extension</td>
<td>10 lb</td>
</tr>
</tbody>
</table>

A built-in compressive stress of 10 lb must be overcome to extend the spring a minimum finite distance.

A tension force of 32.7 lb is developed by stretching the spring 17 in. This provides an average accelerating force of 28.7 lb over the 6 in. acceleration distance. The acceleration of the airfoil is given by

\[
F = F_M - \int_0^L \left( \frac{M_s x}{L} \right) a \, dx = M_s a
\]

\[
= F_M - \frac{1}{2} M_s a = M_t a
\]

where \(F\) is the force available to accelerate the airfoil and carriage

\(F_M\) is the force exerted by the spring

\(M_s\) is the mass of the spring

\(M_t\) is the mass of the airfoil, carriage, and release mechanism

and \(a\) is the acceleration.

Therefore

\[
a = \frac{F_M}{M_t + \frac{1}{2} M_s}
\]
For an initial spring extension of 17 in., the average value of $F_M$ is 28.7 lb, and the average acceleration is 11.8 g. For the minimum spring extension of 6 in., required for acceleration through one chord length, the average value of $F_M$ is 14 lb and the average acceleration is 5.8 g. To obtain lower accelerations, the carriage is arranged so that mass can be added to it. An added mass of 11.5 lb is required to reduce the acceleration to 1 g.

To determine accurately the accelerations actually obtained, moving pictures of the airfoil were taken during a series of tests using a Fastex camera arranged to expose 35 frames in 1/120 sec. The tests were made at an initial spring extension of 17 in. (see first computation, above), and the photographic record showed an actual acceleration of 11.4 g. The difference of 0.4 g from the calculated value is attributed to:

1. the six nylon pulleys in the system whose rotary inertia was neglected in the computation,

2. errors of measurement of the photographs, which showed some scatter,

3. friction in the system.

No detectible decrease of speed during the coasting part of the motion was indicated by the movies, so it is concluded that item 3 is quite small if not entirely negligible.

1.4 TEMPERATURE AND HUMIDITY MEASUREMENTS

In general the rate of flow of water substance into the bottom of the cloud chamber and the temperature profile of the chamber were so related that stable clouds were confined to the lower part of the chamber. By means of measurements of the wet bulb and dry bulb temperatures above the cloud and the temperature at various levels in the cloud, it is possible to calculate the liquid water content at these levels. Eleven thermistors were installed for this purpose along a vertical line 6 in. from the back of the chamber and 12 in. from the side walls. In addition, a wet-bulb and a dry-bulb thermistor were installed at the top center of the chamber. An additional thermistor was placed outside the chamber at a level of 4 ft to monitor the room air temperature. Comparisons between room and chamber temperatures are especially important in evaluating the wall effects within the chamber.

The thermistors were calibrated by means of a constant temperature bath which was first cooled to 0.1°C by use of ice, and then allowed to warm in room air. A total of sixteen readings were thus made for each thermistor over the range from 0.1°C to 22.0°C. From these data, averaged for all the thermistors, the calibration curve (Fig. 1.1) was prepared. In addition, it was possible from these data to derive nominal additive corrections for each thermistor (Table 1.1). Although the correction values for some of the thermistors showed
a tendency to change more or less systematically over the range of temperature considered, the constant additive correction was adopted for the present purpose.

Table 1.2 gives the results of measurements made with the chamber in operation. The dry- and wet-bulb measurements were made just below the exhaust fan at a position about 16 in. above thermistor no. 1. Values are given for the readings with and without the exhaust fan running, the thought being that improved ventilation should give a more reliable wet-bulb measurement. It is our conclusion, however, that the readings taken without the fan running better represent the condition of the chamber, for the following reasons:

1. the cloud top was observed to lie near the level of thermistor no. 3, and for this to be true, a small residual of liquid water above the saturation mixing ratio is required;

2. the thermistor is small enough in thermal mass in relation to surface area that a relatively low ventilation speed (i.e., that provided by the forced feed of cold, cloud-laden air from below) might suffice to give a correct wet-bulb reading;

3. the exhaust fan consistently induced turbulence throughout the chamber, and quite probably was capable of drawing room air into the upper part of the chamber.

The liquid water profile of the cloud (right hand column, Table 1.2) is therefore computed assuming that the total (liquid plus vapor) mixing ratio was constant from the bottom to the top of the chamber in its non-turbulent regions.

**TABLE 1.1**

**CORRECTIONS TO BE APPLIED TO METER READINGS OF INDIVIDUAL THERMISTORS**

Thermistors are numbered in order of descent from the top of the chamber.

<table>
<thead>
<tr>
<th>Thermistor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction</td>
<td>0</td>
<td>+1.0</td>
<td>0</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td>0</td>
<td>+0.5</td>
<td>-0.5</td>
<td>0</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

1.5 **OPERATION OF THE CHAMBER**

Visual observation of the central parts of the cloud was made possible by selective illumination of a narrow slice near the middle of the chamber. Macroscale photography in support of these visual observations was judged to be infeasible because of the low contrast available even with the best lighting.
Fig. 1.1. Calibration of thermistor meter scale.
<table>
<thead>
<tr>
<th>Thermistor No.</th>
<th>Meter Reading Correction</th>
<th>Temp, °C</th>
<th>Water Vap., gr/kg</th>
<th>Liq. Water, gr/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91</td>
<td>17.5</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>88</td>
<td>16.5</td>
<td>11.4</td>
<td></td>
</tr>
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<td>3</td>
<td>86</td>
<td>15.5</td>
<td>10.6</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>85</td>
<td>14.2</td>
<td>9.7</td>
<td>1.1</td>
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<td>5</td>
<td>83</td>
<td>13.1</td>
<td>9.1</td>
<td>1.7</td>
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<tr>
<td>6</td>
<td>78</td>
<td>11.0</td>
<td>7.9</td>
<td>2.9</td>
</tr>
<tr>
<td>7</td>
<td>74</td>
<td>8.8</td>
<td>6.8</td>
<td>4.0</td>
</tr>
<tr>
<td>8</td>
<td>69</td>
<td>6.5</td>
<td>5.7</td>
<td>5.1</td>
</tr>
<tr>
<td>9</td>
<td>64</td>
<td>3.4</td>
<td>4.7</td>
<td>6.1</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>1.6</td>
<td>4.2</td>
<td>6.6</td>
</tr>
<tr>
<td>11</td>
<td>59</td>
<td>0.8</td>
<td>3.8</td>
<td>7.0</td>
</tr>
<tr>
<td>dry</td>
<td>96 (98)</td>
<td>20.1 (21.1)</td>
<td>5.8 (10.8)</td>
<td></td>
</tr>
<tr>
<td>wet</td>
<td>83 (91)</td>
<td>13.4 (17.5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the course of the observations it was determined (1) that it was not possible to produce a non-turbulent cloud when the exhaust fan (at the top of the chamber) was running; (2) that when the air flow into the chamber exceeded a certain speed the cloud became turbulent; (3) that at certain relatively slow rates of air flow, with the exhaust fan not running, a very stable cloud was formed in the central part of the chamber; (4) that turbulence in a thin layer along the walls was present under nearly all operating conditions, i.e., no condition of operation was found in which no wall turbulence was present; (5) that under the stable cloud conditions there was a tendency toward a slight drift of the cloud with a superposed random motion of individual droplets; (6) that a large vortex was generated upon release of the airfoil through the stable cloud, and that the central region of the vortex tended to become nearly devoid of drops.
CHAPTER 2

OBSERVATION OF THE CLOUD

2.1 THE PROBLEM

It is desired to observe and measure cloud droplets within the laboratory cloud with sufficient accuracy to determine whether coalescences are produced by introduced disturbances in sufficient number to establish statistical reliability; but it is necessary to do this without introducing extraneous effects of turbulence or of heating or cooling.

2.2 OILED SLIDE IMPACTION SAMPLING

The bulk of cloud droplet data that have been reported in the literature have been collected by an impaction technique from airplanes flying through natural clouds. Most successful has been the technique of Diem in which the droplets impinge upon a slide coated with an oil film. The oil then serves to reduce the evaporation rate of those droplets which penetrate its surface film. Consideration of the slide dimensions in relation to aerodynamic effects is necessary to evaluate the collection efficiencies for droplets of various sizes. It is also very important that the elapsed time between collecting a sample and making a measurable record of it must be held to a minimum.

The Houghton cloud-droplet camera was designed as the collecting-recording unit for such a sampling system. We were able to borrow this unit from the Department of Meteorology, Massachusetts Insititue of Technology. Unfortunately, our laboratory situation was not at all similar to the airplane-in-cloud situation for which this unit was designed. In the laboratory, the first problem is that of providing an adequate and known impaction speed. Study of the aerodynamics of 1-mm-square and 1-mm-diameter cylindrical rods gave the following collection efficiencies for 20 μ-diameter water droplets:

<table>
<thead>
<tr>
<th>U, m/sec</th>
<th>1.0</th>
<th>2.0</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod, %</td>
<td>84</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Cylinder, %</td>
<td>63</td>
<td>79</td>
<td>88</td>
</tr>
</tbody>
</table>

Analysis of the penetration of an oil surface film by the droplets gave the following results:

| Droplet diameter, microns | 4 | 6 | 8 | 15 | 20 | 30 |
| Penetration speed (minimum), m/sec | 3.87 | 3.18 | 2.74 | 2.00 | 1.73 | 1.41 |
Penetration of the oil film is essential to provide any protection against evaporation. In this range of drop size, the time for complete evaporation in 95% saturated air at 20°C ranges from about 0.2 to 11 sec. This time is obviously increased at lower temperatures, and decreased at lower humidities. The logistics of obtaining a proper sample on the oiled slide and transferring this to the microcamera for photographic recording are difficult. The sampling slide must pass just once through the cloud at a constant speed of about 2 m/sec. It must then be transferred from the chamber to the photographic jig and photographed within a fraction of a second. We have considered carefully how to do this, and concluded that any arrangement capable of meeting the logistic requirements would require appreciable additional development. The violence that this method would do the cloud was also considered a disadvantage.

2.3 TELEMICRO-PHOTOGRAPHY

An alternative, and hopefully superior, method for monitoring the cloud droplet spectrum during our experiments is that of photographing the cloud droplet population in situ without mechanical disturbances of any kind. The method envisioned to do this utilizes the principle of the telephoto technique inversely, by interchanging the object and image distances. It thus becomes possible to photograph a small object (droplet) at a distance of 6 to 12 in. from a long focal-length lens with magnification by use of a very long image distance. For convenience, this method will be called "telemicrophotography."

The particular application envisioned in the present case is quite different from previously reported uses⁴,⁵,⁶,⁷ of the method, although that of Fleckerman and Hanson⁴ has many of the desired features.

The problem is to record cloud droplets photographically down to about 20 μ diameter with sufficient resolution so that size distribution data may be extracted conveniently from the photographs. A working distance of 6 in. or more (up to 12 in.) is required to avoid mechanical interference with the cloud and to permit examination of the cloud in a region beyond the penetration of the wall effects of the cloud chamber. Optical magnification of the image is required to achieve a satisfactory ratio of image size to photographic grain size.

The feasibility of this method was investigated by studies of available lenses, of the means of illuminating the droplet field, and of the number of photographs required to obtain an adequate droplet-size distribution.

2.3.1 Choice of Objective Lens.—Preliminary experiments using a nominal 6 in. focal length f/4.5 lens, adjusted to give a 4:1 to 6:1 optical magnification were suggested as an initial step. It was decided to use a conveniently available 4 x 5 in. cut film emulsion such as Kodak Super Panchro Press Type B for
these experiments. Illumination was adjusted experimentally to give maximum contrast.

Such experiments were performed using Carl Zeiss Tessar Lens No. 2367659 (f/4.5, f = 13.5 cm). Optical magnification was about five, and the lens was used at full aperture. Despite the exercise of great care in this experiment, the best photographic images were of poor quality, and the minimum measurable droplet size was about 40 μ diameter.

Investigation of the photographic images under the microscope indicated that the grain size was not the limiting factor affecting the droplet-size resolution. A more detailed examination of the limits imposed by the diffraction produced by a finite circular aperture and by the aberrations of practical lenses used at appropriate conjugate ratios was therefore undertaken.

The fundamental limitation on the resolving capabilities of a geometrically perfect optical system is that of diffraction in the image due to the wave nature of light and affected by the shape and size of the optical aperture. A point source of light is imaged as an Airy disk due to diffractions if the geometrical aberrations are negligibly small. Furthermore, the images of two neighboring point sources conventionally are said to be resolved if the centers of the corresponding Airy disks are separated by at least the radius of the first dark ring. In the present case, it is desirable to image small cloud droplets while preserving their essential features of size and shape. This implies that the image of the smallest droplet should be approximately an order of magnitude larger than the Airy disk.

According to the above conventional resolution criterion, two neighboring point objects are just resolved if:

$$\frac{S_1 S_2}{n} = \frac{0.61 \lambda}{\sin \theta} \cos \theta'$$

(1)

where $S_1 S_2$ is the linear separation of the two point objects

$\lambda$ is the wavelength of light

$n$ is the index of refraction in the object space

$\theta$ is the half-angular extent of the entrance pupil as seen from the object position

$\theta'$ is the half-angular extent of the exit pupil from the position of the image.

For our purposes, let
\[ \lambda = 0.589 \mu \text{ (sodium D line)} \]

\[ n = 1.000 \text{ (object space filled with air)} \]

\[ \sin \theta = 0.08854 \]

\[ \cos \theta' = 0.9998 \]

Assuming a lens of 13.5 cm focal length and f/4.5 aperture operated at four times magnification in the image space. The corresponding value is

\[ \frac{S_1}{S_2} = 4.06 \mu \]

which is roughly five times smaller than the assumed average diameter of the droplets to be photographed. Thus, from a diffraction standpoint, 20 \( \mu \) droplets ought to be imaged well enough to permit measurement although the image would not be of highest quality.

If the same lens were stopped down to f/8.0 then

\[ \frac{S_1}{S_2} = 7.18 \mu \]

and the image of a 20 \( \mu \) droplet would be expected to be rather poorly defined.

Upon examination of Equation (1), it is found that only the wavelength, \( \lambda \), and the angular extent of the entrance pupil, \( \theta \), can be changed significantly, and that an increase of \( \theta \) or a decrease of \( \lambda \), or both, should lead to improved resolution.

Restriction of the illumination to shorter wavelengths by the use of blue filters or photographic emulsions sensitive only to blue light will bring about some improvement but hardly as extreme as a factor of two. Likewise, \( \sin \theta \) can be increased by using a lens of larger aperture, but these are scarce in a six-inch focal length size which is necessary to maintain a long working distance. (Microscope objective lenses often have \( \sin \theta \)'s of 0.85 and greater but are unsuitable for present purposes because of short working distance and very limited field of view.)

In any case, the above considerations indicate that diffraction could not be the factor limiting the resolution to drops of 40 \( \mu \) diameter or larger. It was necessary therefore to examine the lens used for residual aberrations. Such aberrations depend upon lens design, the conjugate ratio at which the lens is used, the lens aperture, manufacturing accuracy, and frequently, the care with which the lens has been handled. As a result, theoretical treatment of the prob-
lem is impractical. Hence, some simple experiments were carried out to determine how well various lenses could image details of the order of 20 μ when operated at 4:1 conjugate ratio.

The most immediately available test object was a transmission grating having equal line and space widths of about 95 μ. This was illuminated by transmission and the lenses arranged to yield a 4 times demagnified image of the grating which image was then examined through a high quality microscope. Thus, the ability of the lenses to render 24 μ wide lines was assessed visually with rather surprising results:

1. Carl Zeiss, Jena, Tessar Lens No. 2367656, f/4.5, f = 13.5 cm (mentioned above).

A considerable loss of image contrast at f/4.5 was noted, and maximum contrast was achieved only after stopping down to f/8. Even at this aperture, the lines were not as sharp as desired, probably because of the beginning of diffraction effects (note above).

2. Graflex Optar Lens, f/4.7, f = 13.5 cm.

Contrast at full aperture somewhat better than the Tessar above, but behavior was generally similar. Full contrast obtained only by stopping down to about f/8. Position of best focus shifted 0.16 mm toward the lens as it was stopped down from f/4.7 to f/8, suggesting aberration effects.

3. Wollensak Enlarging Velostigmat Lens, f/4.5, f = 16.2 cm.

Very poor at full aperture showing both complete loss of contrast and large focal shift. Contrast improved by stopping down to f/11, but still not really good.

4. C. P. Goertz "Red Dot" Artar (Apochromat) Lens No. 787428, f/9, f = 6 in.

Contrast and imagery very good at full aperture. Perhaps slightly more veiling glare at full aperture than when stopped down. Contrast essentially constant as aperture is reduced; however, diffraction limitation soon enters because the aperture is small to start with.

5. Schneider-Kreuznach Componon Lens No. 4864149, f/4, f = 5.0 cm.

Almost perfect contrast at full aperture and negligible change of focus and contrast as aperture is reduced. Impressive image quality.
These image quality observations served to indicate the source of the 40 µ limitation of resolution found earlier. This was very likely attributable to residual aberrations of the Tessar lens. There seemed little point in trying to double the resolving power by reducing the aperture of that lens.

Both the Tessar and the Optar are based upon the general Tessar lens design, and are probably computed for use at near-infinity object distances. Thus, in the experiments cited above, they are operated at conjugate ratios greatly different from those designed for, and poor imagery is the result. A characteristic of the Tessar formula is that it is unsymmetrical and relatively intolerant of conjugate ratios different from those used in the design.

The last three lenses, i.e., Velostigmat, Artar and Componon, are all derived from a four-lens symmetrical combination designated as a Gauss system of the first type. Such a system generally exhibits a wide tolerance for non-design conjugate ratios and furthermore, since these particular lenses are intended for enlarging or photo-engraving applications, they have been specifically designed for a conjugate ratio near 4:1. The extremely poor imagery of the Velostigmat must be blamed on poor design or workmanship.

The use of a transmission grating as a test object is not completely fair, since conceivably a repeating pattern might be rendered somewhat better than isolated pairs of point objects. Nevertheless, the test gives a good qualitative impression of the ability of the lens to render fine detail of about 20 µ size. For example, the aerial image quality of the Componon lens was so perfect that one would immediately conclude that even 10 µ wide lines or finer could be rendered clearly.

These studies therefore led to the conclusion that diffraction effects should be sufficiently small to permit adequate photographic rendering of droplets in the 20 µ diameter region. Practical attainment of this aim appears to require careful selection of a suitable photographic objective. High-quality enlarging lenses or other lenses designed for 4:1 to 6:1 conjugate ratio and having a usable aperture of the order of f/4.5 appear to be best for this application.

A survey of the market led to the following information:

1. The Super Faron F/0.87 Lens, f = 7.6 cm can be supplied corrected for 4:1 conjugate ratio and for a specified thickness of plane glass window (wall of cloud chamber) to resolve at least 100 lines per mm, at about $1500. Question about working distance. Farrand Optical Co., Inc., New York 70, New York.

3. We have the best information about the Schneider-Kreuznach Componon Lens series, and at least two of the series were available for preliminary testing. Data on this series of lenses are as follows:

<table>
<thead>
<tr>
<th>Focal length</th>
<th>Aperture</th>
<th>Approximate Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0 cm</td>
<td>f/4.0</td>
<td>$55.00</td>
</tr>
<tr>
<td>10.5 cm</td>
<td>f/5.6</td>
<td>70.00</td>
</tr>
<tr>
<td>15.0 cm</td>
<td>f/5.6</td>
<td>80.00</td>
</tr>
<tr>
<td>18.0 cm</td>
<td>f/5.6</td>
<td>99.00</td>
</tr>
<tr>
<td>21.0 cm</td>
<td>f/5.6</td>
<td>124.50</td>
</tr>
</tbody>
</table>

Because of the relatively nominal prices of the Componon lenses, and the excellent qualities shown in the experimental test of the f/4, f - 5.0 cm Componon (above), it was decided to borrow an 18.0 cm f/5.6 Componon, known to be available within the University, for testing.

The 18.0 cm Componon lens was compared against the 5.0 cm Componon discussed above for ability to resolve details of the transmission grating used in the earlier experiments. In this case the 5.0 cm lens was stopped down to f/5.6, the maximum aperture available for the 18.0 cm lens. The resolution and contrast obtained was not discernibly different between these two lenses, and was far better than anything achieved with the other lenses tested. A few photographs were made using a microscope slide sprinkled with glass beads as an object. In this situation, having a stationary object and the best possible focus, 20 μ diameter beads were readily resolved, and the limit of resolution was near 10 μ diameter. On the basis of these results it was decided to purchase a 21.0 cm or an 18.0 cm Componon lens depending upon their relative performance in our situation. The 21.0 cm lens was finally purchased. The telemicro-camera was then constructed in the form of a long box having this lens mounted at one end, and a 5 x 7 plate holder at the other, the distance from lens to plate being about 5 ft, and the magnification being five fold.

2.32Number of Droplets per Photograph.—The focal field is to be observed through an intervening portion of the laboratory cloud. Two questions arise: (1) how many droplets should ordinarily be found in the focal field of the camera, and (2) how many of these droplets will be occulted by intervening cloud droplets.

Consider a monodisperse cloud composed of 20 μ diameter droplets in concentrations of \(10^{-3}\), or a liquid water content of about 4 gm m\(^{-3}\). A 150 mm long path (from chamber wall to object plane) contains 150 of these droplets per mm\(^2\) of viewing area, and the total optical cross-section of these droplets is 0.047 mm\(^2\). This means that most of the time no more than 4.7 percent of the area of the focal plane will be occulted by droplets in the viewing path.

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The depth of field under these circumstances is of the order of 0.05 mm. If the field of view is a 1 in. diameter disk of this thickness, the expected number of droplets in the field of focus is 25. Of these 5 percent are expected to be occulted, hence 23 or 24 useful images should be obtained on each photograph.

Depending upon the variability of the droplet sizes in the cloud, an adequate size spectrum representation will require a number of photographs. On the basis of these estimates, it appears that effort should be directed toward using a larger diameter field on the one hand and that some means of obtaining a rapid succession of photographs of different fields may be desirable.

The illumination technique may contribute to the solution of this problem. Obviously, the drop images from the 25 or so drops caught in a single photo field must occupy a very small fraction of the useful area of the photo-negative. It is therefore highly likely that the images formed by a second drop field, different from the first, which can be obtained by a movement of the camera of .002 in. along the optic axis, will fall on different portions of the film. This can be done if the illumination is controlled so that no general "fogging" of the film is produced by each exposure.

2.3 Illumination.—An illumination scheme capable of providing the multiple exposure required might be devised on the basis of 90° reflection if adequately intense sources can be obtained. Such a scheme is diagrammed in Fig. 2.1.

Parallel beams of light, shaped by slits to rectangular cross-sections, and filtered through water cells to reduce thermal effects in the cloud, enter the chamber from opposite sides (Fig. 2.1). One slit is much longer than the other so as to give an asymmetric pattern. This asymmetry is useful in the analysis of the photographic images. The distance between the two opposing spots in each drop image provides a baseline for measurement of the image.

The feasibility of this system was tested using the Sylvania C-100 concentrated arc lamp with which we have had experience. Two such lamps were arranged with optics at hand to approximate the situation diagrammed in Fig. 2.1.

Several attempts were made to photograph the cloud droplets with this system, but success was not achieved. The illumination was apparently insufficient even to produce images on Polaroid ASA 5000 film. Further study of this problem is appropriate, because the illumination appears not to be that weak relative to beams which produced good glass bead images in earlier tests. Another possibility is that the cloud droplets may have been a good deal smaller than 20 μ in diameter.

Further experimentation has been suspended; however, it should be emphasized that bright field photography can be used if finally it is determined that the dark field, 90° reflection arrangement is completely impracticable. 4
Fig. 2.1. Diagram showing the illumination scheme for cloud-monitoring photography and the geometry of the droplet images produced by the system.
The bright field method will not allow the superposition of several images, discussed above, and it is anticipated that the data so obtained will be more difficult to interpret, but it should serve our purpose more adequately than any mechanical sampling method currently available.
CHAPTER 3

ANALYSIS OF VORTEX EFFECT UPON DROPLET MOTIONS

3.1 INTRODUCTION

It is well established that coalescence of cloud droplets is necessary for the production of rain.\(^1\) Whereas diffusion theory indicates that the size distribution of cloud droplets should become increasingly narrow with time, observations show the opposite tendency. Especially the course of development of cumulus clouds and the parallel course of development of their droplet-size distributions indicate that the presence of air turbulence may be an important factor in producing the observed broadening of the cloud droplet spectrum. Other factors such as electric charge and phase change effects upon surface properties of droplets are probably also of great importance. The present research is directed toward the evaluation of turbulence as a means of bringing cloud droplets together and thus promoting coalescence.

The present experimental approach to the problem is based upon the assumption that the collision-producing effects of air turbulence, which depend upon the ability of turbulent forces to produce velocity differences between adjacent cloud particles can be modeled in terms of the effects of a cylindrical vortex. An analysis of this model was begun by means of analog computer technique.

Consider an isolated steady state vortex having a velocity field of the form

\[ v_t = \frac{\Gamma}{2\pi r} = \frac{a}{r} \quad (2) \]

where \( \Gamma \) is called the strength of the vortex and is equal to the circulation around it

\[ \Gamma = \oint V_i \cos(\psi_i, ds) \, ds, \]

and \( r \) is the radius of the vortex.

3.2 THEORETICAL ANALYSIS

Consider an isolated steady state vortex having a velocity field of the form
\[ U_t \propto R \text{ for } 0 \leq R < b \quad (3) \]

and

\[ U_t \propto \frac{1}{R} \text{ for } b \leq R, \quad (4) \]

where \( U_t \) is the tangential velocity of the vortex at radius \( R \), is the radius of maximum \( U_t \) at which the two vortex regimes meet.

The strength of a vortex is generally taken as its circulation

\[ \Gamma = \oint U_1 \cos(U_1 ds) ds, \quad (5) \]

and the second form of vortex motion is frequently expressed as

\[ U_t = \frac{\Gamma}{2\pi R} \quad (6) \]

If a vortex characterized by (3) and (4) is introduced into a space, large compared to the vortex, in which a uniform distribution of cloud droplets exists prior to the introduction of the vortex, then the droplet population will be re-distributed. It is convenient to express the force field in cartesian coordinates:

\[ F_x = m \ddot{X} = D(U_x - \dot{X}) \cdot |\dot{U}_x - \dot{X}| \quad (7) \]

\[ F_y = m \ddot{Y} = D(U_y - \dot{Y}) \cdot |\dot{U}_y - \dot{Y}| - g \quad (8) \]

\[ D = \frac{C_D \rho \sigma}{2}, \quad R = \sqrt{X^2 + Y^2} \]

\[ \dot{U}_x = U_t \cos \theta = U_t \frac{X}{\sqrt{X^2 + Y^2}} \]

\[ \dot{U}_y = U_t \sin \theta = U_t \frac{Y}{\sqrt{X^2 + Y^2}} \]

Here it is assumed that the only forces exerted upon the droplets are the aerodynamic drag forces attributable to differences of speed between the air and the droplets.
\( C_D \) is the drag coefficient

\( \sigma \) is the cross-sectional area of the droplet

\( \rho \) is the density of the air

\( U_X, U_Y \) are the X and Y components of air velocity

\( \dot{X}, \dot{Y} \) are the X and Y components of velocity of the droplet,

\( \ddot{X}, \ddot{Y} \) are the X and Y components of the acceleration of the droplet

and \( F_X, F_Y \) are the X and Y components of force upon the droplet.

The operation \((U_X - \dot{X}) \cdot |U_X - \dot{X}|\) indicates that the sign of the difference must be considered in determining the direction in which the drag force acts, and is indicated by \([U_X - \dot{X}]^2 (\text{sgn})\) in the following material.

For analog computation, it is helpful to reduce all variables to non-dimensional form. This may be done by introducing the arbitrary length scaling factor \( L \), and the arbitrary time scaling factor \( \tau \):

\[
\begin{align*}
x &= \frac{X}{L}, & y &= \frac{Y}{L} \\
\dot{x} &= \frac{\dot{X}}{L}, & \dot{y} &= \frac{\dot{Y}}{L} \\
\ddot{x} &= \frac{\ddot{X}}{L}, & \ddot{y} &= \frac{\ddot{Y}}{L} \\
\end{align*}
\]

\[ (9) \]

\[
\begin{align*}
\gamma &= \frac{R}{L}, & \gamma &= \frac{\Gamma}{L^2} \\
d &= D \cdot L, & U_X &= U_X \frac{T}{L} \\
a &= A \tau, & U_Y &= U_Y \frac{T}{L} \\
\end{align*}
\]

The relationship of the components of position and velocity for a counter clockwise vortex is shown by reference to Fig. 3.1.
Fig. 3.1 The relationships between position and velocity components for a counter clockwise vortex.

In respect to angles measured counter clockwise from the +x axis, $U_x$ is proportional to the negative sine function, and $y$ is proportional to the positive cosine function. As a result, for the inner vortex, $R < b$:

$$U_x = A R \cdot \left( - \frac{Y}{R} \right) = -AY$$

$$U_y = A R \cdot \left( + \frac{X}{R} \right) = +AX;$$

and for the outer vortex, $R \geq b$:

$$U_x = \frac{\Gamma}{2\pi R} \cdot \left( - \frac{Y}{R} \right) = -\frac{\Gamma}{2\pi} \frac{Y}{R^2}$$

$$U_y = \frac{\Gamma}{2\pi R} \cdot \left( + \frac{X}{R} \right) = +\frac{\Gamma}{2\pi} \frac{X}{R^2}$$

Equations (7) and (8) may now be written in nondimensional form:

$$\dot{x} = \frac{d}{m} \left( U_x - \dot{x} \right)^2 \left( \text{sgn} \right)$$

$$\dot{y} = \frac{d}{m} \left( U_y - \dot{y} \right)^2 \left( \text{sgn} \right) - \frac{r^2}{L} g$$

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or
\[ \ddot{x} = \frac{d}{m} (-ay - \dot{x})^2 \text{ (sgn)} \]  
(10a)

\[ \ddot{y} = \frac{d}{m} (ax - \dot{y})^2 \text{ (sgn)} - \frac{r^2}{L} g \]  
(11a)

for the inner vortex, and

\[ \ddot{x} = \frac{d}{m} \left( -\frac{x}{2\pi r} - \dot{x} \right)^2 \text{ (sgn)} \]  
(10b)

\[ \ddot{y} = \frac{d}{m} \left( \frac{x}{2\pi r} - \dot{y} \right)^2 \text{ (sgn)} - \frac{r^2}{L} g \]  
(11b)

for the outer vortex regime.

3.3 ANALOG COMPUTATIONS

Equations (10a,b) and (11a,b) were solved by electronic analog computer. The analyzer diagram is shown in Fig. 3.2.

Values for the scaling factors, \( \tau \) and \( L \) must be fixed to produce the appropriate analog solutions. A tangential vortex speed of 25 cm/sec was chosen for the transition radius, \( b \), and a value of 0.1175 sec was chosen for \( \tau \) in consideration of computer-plotter characteristics. These choices lead to the necessary numerical values:

\[ U_0(b) = 25 \text{ cm/sec} \]
\[ \tau = 0.1175 \text{ sec} \]
\[ L = b = 2.94 \text{ cm} \]
\[ \frac{r^2}{L} g = 4.602. \]

Results of the analog computations are presented in Figs. 3.3 - 3.9. The problem was worked through for drop sizes of 20 \( \mu \), 30 \( \mu \) and 50 \( \mu \) radius. Characteristics of these droplets are given in Table 3.1.

3.4 CONCLUSIONS

Figures 3.7, 3.8 and 3.9 serve to emphasize that a simple cylindrical vortex
TABLE 3.1

CHARACTERISTICS OF WATER DROPLETS

Radius, \( r \); terminal fall speed, \( v_t \); terminal fall speed scaled for input to the computer, \( \dot{y}(0) \); \( C_D \rho \sigma/2m \); and \( D/m \) scaled for input to the computer.

<table>
<thead>
<tr>
<th>( r ), microns</th>
<th>( v_t ), cm/sec</th>
<th>( \dot{y}(0) )</th>
<th>( C_D \rho \sigma/2m )</th>
<th>( D/m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>27</td>
<td>1.079</td>
<td>1.18</td>
<td>.402</td>
</tr>
<tr>
<td>30</td>
<td>10.8</td>
<td>.432</td>
<td>3.27</td>
<td>1.11</td>
</tr>
<tr>
<td>20</td>
<td>4.8</td>
<td>.192</td>
<td>7.46</td>
<td>2.54</td>
</tr>
</tbody>
</table>

serves to concentrate droplet populations as long as the terminal fall speeds of the droplets are less than the maximum tangential velocity of the vortex motion. The effect is greatest for the smallest droplets, and may therefore be particularly significant in the early stages of broadening of cloud droplet size spectra.

The interaction of adjacent vortices should enhance the effect indicated.

Whether vortices of the strength and scale postulated occur in the free atmosphere is not established. This can be determined conclusively only by a suitable measurement program.
Fig. 3.2. Analog computer diagram for solution of Equations (10 a, b) and (11 a, b).
Fig. 3.3. Trajectories for droplets of 20 μ radius initially at rest in a rectilinear vortex. Drops at a, b, c, and d are initially at rest along the line \( x = 0, \ y > 0 \). Drops e and f are initially at rest along the line \( y = 0, \ x > 0 \). Radial distance \( L \) is equal to 2.94.
Fig. 3.4. Plot of x and y components of velocity for 20 μm radius droplets initially at rest in a rectilinear vortex. Initially position of the drop for curve no. 1 is x(0) = -0.1, y(0) = 0; no. 2 is x(0) = +0.1, y(0) = 0; no. 3 is x(0) = +0.5, y(0) = 0. Origin of all three curves at 0,0, and sense is counter clockwise. The points numbered 1 through 10 on curve no. 3 are time marks and are derived from Fig. 3.5 by measuring $\dot{x}$ and $\dot{y}$ at constant time intervals (integral multiples of τ) and replotted these values on Fig. 3.4.
Fig. 3.5. Plot of x and y components of velocity for 20 μ radius droplets initially at rest. Number in parentheses gives initial x-coordinate of droplet, y-coordinate was 0 in each case.
Fig. 3.6. Plots for droplets initially at (-0.1, 0), of x (line no. 1) and y (line no. 2); and for droplets initially at (+0.5, 0), of x (line no. 3), and y (line no. 4).
Fig. 3.7. Plot for droplets of 20 radius initially on the line "A-A" and moving in the -y direction at their terminal fall speed. The numbers -40 to +40 are values of $X_0$. The distortion of the initial drop field is shown. Note that drops whose $X_0$ coordinate is $+23$ are displaced to the -x side of the vortex, and return to the +x side below the vortex. This plot shows most clearly the removal of drops from the vortex core.
Fig. 3.8. Plot similar to Fig. 3.7 for droplets of 30 μ radius. The clear area is still apparent by the $X_0$ coordinate for the dividing line is near +19 rather than +23.
Fig. 3.9. Plot similar to Fig. 3.7 for droplets of 50 μ radius. Note that the terminal fall speed of these droplets (27 cm/sec) exceeds the maximum postulated value of $U_0 (25$ cm/sec).
CHAPTER 4

PROJECT HI-CUE 1959 PARTICIPATION*

4.1 INTRODUCTION

Project Hi-Cue has been a continuing cooperative research effort, coordinated by the Cloud Physics Laboratory, GRD, and engaging in a series of comprehensive field observations of convective storms near the San Francisco Peaks, Flagstaff, Arizona, since 1958. In the spring of 1959, The University of Michigan was invited to participate in this program, using the van-mounted APQ-40 radar which had been acquired under Contract No. AF 19(604)-2176 in 1958. The results of this particular effort are the subject of the present chapter.

4.2 DESCRIPTION OF THE AN/APQ-40 RADAR (MODIFIED)

The AN/APQ-40 radar was developed as an airborne weather reconnaissance radar by the Glen L. Martin Company under contract with the U. S. Air Force. A prototype model was constructed and delivered but it was never operationally employed as an airborne unit. The University of Michigan acquired the radar under Contract AF 19(64)-2176 during 1958.

An extensive redesign and modification of the AN/APQ-40 was accomplished to provide a radar suitable for surface weather surveillance in field-type programs. Major components of the radar were mounted in an SCR-584 fire control radar van in which the antenna control system of the SCR 584 was retained. Completely self-contained operation in the field is attained by use of a gasoline engine-powered generator as a power source.

Characteristics of the AN/APQ-40 as modified are as follows:

Transmitter Frequency 9.375 Kmcps ± 50
Transmitted Power (Peak) 2.5 x 10^3 watts
Receiver Sensitivity -104 Dbm (approx.)
Pulse Duration 1 microsecond
Pulse Repetition Frequency 300 sec⁻¹
Beam Dimension 1.5° Conical
Polarization Horizontal Linear or Circular
Antenna Scan 360° azimuth at 5 RPM
            -2 to 90° elevation
Indicators 7 and 12 inch PPI

*By Floyd C. Elder
The radar receiver is provided with a gain control adjustable in 11 incremental steps of chosen magnitude. The gain steps are adjusted to selected value, usually in increments of 5 decibels, by use of a signal generator from which a test signal of known power is injected into the receiver. The total dynamic range of the receiver over the 11 calibrated steps is approximately 60 decibels. Absolute calibration of the entire radar system including the antenna and transmission lines was not available during the 1959 measurement program.

4.3 DESCRIPTION OF THE 1959 HI-CUE RADAR MEASUREMENT PROGRAM

The APQ-40 radar was located at the Flagstaff Municipal Airport adjacent to the control center of Project Hi-Cue. Because only one radar was generally available to the project, it was operated in such a manner that its maximum usefulness to the program was attained. This required that the one radar be employed to make several types of measurement and precluded obtaining extended periods of continuous measurements of any single cloud property.

Figure 4.1 is a topographic map of the area in which the observation program was conducted. The locations on the map significant to this report are as follows:

(1) APQ-40 Radar location;
(2) Fort Valley Experiment Station (FVS);
(3) Meteorology Research, Inc., (MRI) radar site; and
(4) Doyle Saddle.

The operation of the radar may be categorized into five different phases, each designed to study a specific aspect of the cloud growth and behavior.

Phase 1. Three-dimensional mapping of precipitation echoes. This phase of observation was designed to map the three-dimensional distribution of precipitation echoes and to maximize the resolution of temporal changes in echo patterns. Throughout this phase of observation, the radar was operated on maximum sensitivity and photographs of the scope were taken for each 360° of antenna scan. Antenna elevation was increased one degree following each scan, commencing with a minimum elevation determined by the ground echo pattern. If precipitation echoes were observed at greater than 20° elevation, the increment of elevation change was increased to 5° or greater. The beam width of the radar is 1.5° to the half-power points. The program of observation provided a total volume coverage throughout the volume of primary interest. The range of observation was determined by the location of significant precipitation echoes but was most frequently chosen as 20 miles to provide the maximum obtainable resolution in space.
Fig. 4.1. Topographic map of the San Francisco mountain area, Flagstaff, Arizona.
Phase 2. Precipitation Echo Reflectivity Mapping. Phase 2 observations were designed to provide measurements of spatial distribution of cloud radar reflectivity. This was accomplished by taking successive scans at constant elevation while reducing the receiver sensitivity by a calibrated increment each scan. The minimum sensitivity at which echoes were detectable gives an objective measure of the cloud reflectivity. Calibration of the radar in absolute terms was not available during the 1959 program.

Phase 3. Echo Area Distribution Mapping. Phase 3 operation gave the aerial distribution of precipitation echoes and movement of echoes in time. It was accomplished by taking successive photographs of the radar scope with the radar operating at maximum sensitivity and at a constant antenna elevation angle, usually near zero degrees. Such observations result in time-lapse pictures of the precipitation cells.

Phase 4. Range-Height Observations. Phase 4 operation consisted of scanning in a vertical plane with the radar antenna at chosen azimuth. This results in a range-height presentation in which the vertical distribution of precipitation echoes is given as a function of range. Cloud reflectivity as a function of height can also be determined through successive scans at different receiver sensitivity settings. Since this type of observation is not economical of time with the APQ-40 radar, only short periods of such observations were accomplished during the 1959 program.

Phase 5. Cancellation Ratio Measurements. Phase 5 observation was an experimental application of a unique feature of the APQ-40 radar. It was possible to select the polarization of the transmitted energy as either linear (horizontal) or circular. This change in polarization will theoretically discriminate between spherical and nonspherical scattering particles. Thus, some determination of the presence of significant amounts of ice in clouds should be possible through measurements of cloud reflectivity by circularly and linearly polarized energy. Several short periods of such observations were conducted.

Summary of Observations (1959).—During the period of Project Hi-Cue, July 14–August 26, 1959, a total of 155 hours of radar observation was obtained. However, the periods of observation were divided among the above listed phases of observation so that only a limited number of continuous periods of data are satisfactory for meaningful analysis. A log of the data collected during the 1959 period of observation is included as Table 4.1.

In addition to the observations described above, a few special experiments were undertaken. One, was an attempt to study the characteristics of air flow within and near developing cumulus by tracking tracer material. An analysis of this experiment is presented below. The material employed as tracer was fiberglass "chaff" that formed a radar target but had a free fall velocity small compared to the air motions experienced near the developing cloud.
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4.4 USE OF "CHAFF" AS A TRACER OF AIR MOTION

The application of radar-reflecting "chaff" to the measurement of atmospheric motions was first reported by Warner and Bowen,9 who studied small scale motions in both the vertical and horizontal planes and obtained a measure of the fine structure of the wind. In 1954, Battan,10 using a technique similar to that of Warner and Bowen, measured the horizontal divergence pattern enclosing a cumulus cloud and also was able to estimate the vertical distribution of divergence by assuming a constant fall velocity for the chaff. Further application to mesoscale measurements was also demonstrated and horizontal wind profiles in a region of strong shear were measured with the chaff technique. In each case, the chaff winds were not only consistent with pilot balloon winds, but yielded a more detailed picture of the wind field.

Use of chaff as a tracer of air movements at high altitudes was demonstrated by Anderson and Hoehne,11 when they showed close agreement between observations of chaff movements and winds measured by conventional rawinonde techniques. Jenkins and Webb12 have since reported successful application of chaff as a wind sensor at altitudes above 140,000 ft.

4.41 Description of Experiment.—During the Hi-Cue program it was desired to measure the characteristics of air movement within and outside the boundaries of the visible cloud. While the project aircraft, which penetrated the clouds during periods of active growth, achieved a measure of vertical acceleration within the clouds, it was believed that a more realistic measure of the magnitude of cumulus convection could be obtained through use of a tracer technique as described by Warner and Bowen. A new type of chaff was used that has a small mass-to-area ratio and a terminal fall velocity lower than that formerly employed. It consisted of cylindrical segments of fiberglass coated with aluminum and cut to a length such that high radar reflectivity is achieved at the wavelength desired. The terminal fall velocity in still air is estimated to be 20-30 ft/min.

The chaff was packaged in small bundles that were easily dispensed through the open window of a small aircraft. Each bundle dispersed sufficiently to be an easily detectable radar target within the average 20 mile range used in the experiment. During the actual operation, the aircraft (a Cessna 172 operated by personnel of Atmospheric Research Group) penetrated a chosen cumulus cloud on a horizontal straight-line path near the base of the cloud. During the traverse, aircraft observers strove to dispense a parcel of chaff just before entering the cloud, one as close as possible to its center, and one just after emerging from the cloud. In some cases, only two parcels were employed; one outside and one within the cloud. Spacing of the chaff parcels was necessarily greater than the minimum resolution of the radar at the range of the cloud which was studied.

Clouds which were chosen for study were in the early stages of development but were believed destined to develop into mature thunderstorms. Due to the re-
strications upon aircraft penetration and because precipitation echoes would mask the chaff echoes, mature thunderstorms were never studied with this technique.

4.42 Method of Observation and Analysis.—The 3 centimeter APQ-40 radar, having a 1.5 degree conical beam, employed in the program of cloud study was also used to observe the chaff. Since it was desired to observe the movements of two or three chaff targets, often located at widely different altitudes, the position of each parcel could not be continuously monitored. Once the chaff was dropped, the radar was operated on PPI scan. The antenna elevation was manually programmed to achieve a sequence of scans beginning about two degrees below the lowest chaff echo. The antenna elevation was increased by one degree steps until the uppermost echo had been detected. Such a program permitted the cycle to be repeated about once each two minutes unless the echoes were very widely separated in elevation. A repeater scope enabled each scan of the antenna to be photographed to provide a record for later analysis. No attempt was made to measure echo power because to do so would have decreased the frequency of observational fixes on the individual parcels by several times and would not have given significantly more information.

The data were analyzed by examining the film record and measuring the range, azimuth, and elevation angle of each detected chaff echo. When a significant degree of diffusion caused the chaff echo to appear at two or more elevation scans, the best estimate of the central location was recorded. However, after a large degree of growth had occurred, the vertical spread of the chaff permitted observation of trajectories at different elevations. This method of observation and analysis permitted a time history of each chaff parcel to be obtained with a time resolution of about two minutes. The results obtained showed a varying degree of success and gave some interesting measurements of air motion in the vicinity of rapidly growing cumulus clouds. However, the analysis discloses some severe limitations to the otherwise practical technique.

4.5 DESCRIPTION OF THE RESULTS

The results of a series of measurements based upon the use of chaff as a tracer of convection will first be presented. These results will illustrate not only the degree of success attained but also the problems encountered. Following the general discussion, a more detailed analysis of the more completely documented case of July 28, 1959 will be presented.

Figures 4.2 through 4.7a present the trajectories of the several chaff parcels dropped from the aircraft and tracked by radar during the period of Project HI-Che, 1959. The upper portion of each figure is a plan view of the trajectory projected onto the horizontal plane of the observing station. The successive fixes are entered as individual points. Each point that represents an elapsed time of ten minutes, or multiples thereof, is emphasized. The lower portion of each figure is a graph of the elevation of each chaff parcel relative to the ob-
observation point versus elapsed time since the parcel was first detected. The estimated center point of each parcel is plotted unless an indication of vertical extent is shown. The winds aloft, as measured by conventional rawinsonde techniques, are also included for the observation time nearest that of the chaff experiment.

Figure 4.2 - July 20, 1959. No precipitation echoes were detected at the beginning of the observation. Parcels No. 1 and No. 2 were dropped into and outside of the visible cumulus cloud, respectively. A precipitation echo that subsequently developed just east of No. 1 parcel, presumably from a different cloud, obscured it after 25 minutes and tracking was discontinued. No. 2 echo ascended rapidly and developed an apparent vertical elongation with time as shown by the dashed lines of Fig. 4.2. A fast southward movement ahead of the precipitation area which engulfed No. 1 was noted. Parcel No. 3 was dropped at a later stage of cumulus development at a higher elevation and was still distinct when observations were terminated.

No conclusive measure of differential convection is evident from this series of observations.

Figure 4.3 - July 24, 1959. No precipitation echoes were detected throughout the period of observation of the chaff movement. No. 2 parcel was dropped within a visible cloud and at an elevation nearly equal to that of Nos. 1 and 3. The reasons for the discrepancy in elevation at the time of first detection are not known. The cloud associated with parcel No. 2 at time of drop did not develop a precipitation echo, a result which is consistent with the apparent downward motion of the chaff parcel within the cloud.

Figure 4.4 - July 28, 1959. Figure 4.4 presents the results of the most successful observation of the program in that a rather complete record of chaff trajectory was obtained during an active phase of cumulus development. Parcels No. 1 and 3 were dropped about 1000 ft from the cloud boundaries, according to pilot estimate, while No. 2 was dropped in an updraft of 1,500 ft/min within the cloud.

Parcel No. 2 was observed on three successive fixes as it rose rapidly within the cloud. It attained an altitude of 17,600 ft in about 5.5 minutes after which it apparently moved away from the axis of vertical air motion and was lost in the developing precipitation echo. Averaged over the 5.5 minutes of observation, a vertical velocity of about 1,500 ft/min is indicated. This observation together with visual photographs of the cloud boundaries has provided information for a separate analysis presented by Anderson. Parcel No. 3 showed a gradual but moderate change in elevation. Some vertical spread of chaff occurred but the central points are plotted here. The horizontal trajectory described an apparent gradual curve around the larger cumulus that developed nearby. After about 46 minutes, parcel No. 3 apparently also became entrained in the precipitation echo.
Fig. 4.2. Chaff trajectory, July 20, 1959.
Fig. 4.3. Chaff trajectory, July 24, 1959.
Chaff Trajectory
July 28, 1959

Fig. 4.4. Chaff trajectory, July 28, 1959.
Fig. 4.5. Chaff trajectory, July 29, 1959.
Fig. 4.6. Chaff trajectory, July 30, 1959.
Chaff Trajectory
July 30, 1959

Fig. 4.6a. Chaff trajectory, July 30, 1959.
Fig. 4.7. Chaff trajectory, August 19, 1959.
Fig. 4.7a. Chaff trajectory, August 19, 1959. Plotted as altitude vs. range from Radar Station.
Parcel No. 1 was apparently dropped in an area not as strongly influenced by the convection of the growing cumulus and its movements consequently conformed more nearly to the general wind field during the early period of observation. The chaff parcel experienced a large amount of vertical diffusion. After about 30 minutes, horizontal shear caused the upper and lower portions to follow separate trajectories. The elevation trajectory shown in Fig. 4.4 represents only the upper portion of the parcel. This portion of the chaff was tracked for a total of 130 minutes to a point 3.6 miles south of the radar station. However, because of difficulty in obtaining fixes at high elevation angles, the accuracy of the later section of the trajectory is doubtful and only the first 65 minutes is shown.

Figure 4.5 - July 29, 1959. Figure 4.5 represents a case where two chaff drops were accomplished at two different elevations in the presence of a strong horizontal wind shear between the two levels. Parcel No. 1 shows a very rapid, although erratic, descent. A precipitation echo developed just west of the chaff echo and the chaff remained in close proximity to the precipitation through the period. The downward motion may have been due to the orographic effects to the lee of the San Francisco Peaks under a rather strong gradient wind. The possibility also exists that the chaff failed to disperse properly, but this is not supported by its initial vertical motions, nor by the interruptions of its later rapid fall rate.

Parcels No. 1a and 2a were dropped at an elevation approximately 10,000 ft higher than No. 1 and show a movement in agreement with the observed wind at that level. A large precipitation echo existed below and to the east of the chaff parcels.

Figure 4.6 and 4.6a - July 30, 1959. Figures 4.6 and 4.6a represent a case where two multiple chaff drops were accomplished, spaced closely in time and location. As will be noted, the chaff movements were in general agreement with the wind and the two successive paths coincided rather closely. In addition, no significant divergence was indicated in either case. A peculiar phase relationship between the vertical motions of the two parcels may be noted in each case. An explanation of such relationships would however, require more accurate and detailed observations. The relation to visible clouds is not known but no precipitation echoes were observed.

Figure 4.7 and 4.7a - August 19, 1959. A very strong wind of 35 to 40 knots existed at the elevation of the chaff drop on August 19. The chaff parcels were dropped about 2,000 to 3,000 ft above the San Francisco Peaks and a few miles downwind. The trajectories described by the chaff were believed to be due to a lee wave existing downwind from the mountain.

Figure 4.7a shows the three trajectories plotted on a range scale to illustrate the close correlation of the trough and crest of the three trajectories. Parcel No. 2 followed No. 1 by about two minutes in time while No. 3 was dropped about ten minutes following No. 1. It appears that the wave has been displaced
toward the southwest by about one mile during this ten minute period.

Cumulus clouds did not exist in the area at the time of this experiment due to dryness of the air mass. However, several standing wave type clouds were present to the lee of the peaks during the morning. No means are available to compare the chaff trajectory with the location of the clouds. This experiment is a further indication of the usefulness of the chaff as a tracer of air movement.

\[ 4.6 \text{ ANALYSIS OF TRACER TRAJECTORIES IN THE VICINITY OF A DEVELOPING CUMULUS CLOUD} \]

The chaff experiment of July 28, 1959, present an excellent opportunity to observe the trajectories in the close proximity of a cumulus cloud during its stage of rapid growth. To the extent that the chaff trajectory represents the air trajectory the behavior of the flow in the vicinity of the cloud is indicated. The results of the observations will be presented and compared, to the extent possible, with the convective cloud model proposed by Newton and Newton.\[14\]

\[ 4.61 \text{ Description of the Experiment.} \]—The observations of July 28, 1959 are briefly described in 4.5 above and the trajectories are shown in Fig. 4.4. The chaff parcels were dispensed from the aircraft about 1000 ft from the boundaries of the visible cloud and within the cloud. The trajectory of the parcel within the cloud has been the topic of a paper (Anderson\[13\]) and will not be discussed here. The trajectories of parcels labeled 1 and 3 in Fig. 4.4 have been examined in the greatest detail possible commensurate with the resolution of the radar observations.

The APQ-40 radar employed in tracking the chaff parcels was limited to PPI search operation. The antenna was programmed manually so that each successive PPI scan was at one degree greater elevation. The range of scan covered the elevations in which chaff or precipitation targets were detected. In most cases the sequence of scan could be completed in about two minutes. Thus, the time resolution of the observations is limited to about this value.

The beam width of the antenna to the half-power points is about 1.5 degrees. Thus, the type of operation described gives some overlap of coverage on two successive scans. In case of a target of large radar cross-section, this factor could lead to detection of the same point target at two different indicated elevations. However, it is believed that subjective elimination of weak echoes in the analysis effectively results in an accuracy of about one degree in the location of the chaff parcels in elevation. Resolution in azimuth is less accurate and is limited by the ability of the analysis to read the azimuth from the PPI scope pictures.

\[ 4.62 \text{ Reduction and Evaluation of Observations.} \]—Each frame of the photographic record was thoroughly examined to obtain the best possible estimate of the mean location of the chaff parcels. The data were then reduced to range and
azimuth relative to the radar site for each 1000 ft increment of elevation. These data are tabulated as Table 4.2 for both No. 1 and No. 3 chaff parcels. Because the rate and amount of vertical diffusion differed for the two parcels, their elevations for the same observation do not coincide.

The individual fixes for each of the parcels at each elevation were then taken as the end points of the trajectory vectors for the chaff during each elapsed time interval. A mean velocity was then computed for each case. This method of analysis assumes that the vertical movement of the chaff during the elapsed time interval was negligible. That is, the chaff observed at one elevation at the beginning of a period is assumed to be the same chaff as observed at that elevation at the end of the period. This is not rigorously true but the error involved in the assumption is small compared to the accuracy of the observations.

The analysis resulted in trajectory velocities averaged over about two minute increments and indicated a very erratic nature with many short period fluctuations. It was believed that these fluctuations were not realistic and were, in fact, due to the inaccuracies in the fixes of the chaff parcels. At each elevation, the chaff represents an extended target sometimes exhibiting a ragged boundary. It was, therefore, difficult to assign an exact azimuth or range to each fix. Since the two minute period between observations represented only a small movement in most cases, a small error in location at either observation would result in a large error in the velocity measurement.

Because of the inaccuracy believed to be present in the short period averages, it was decided to obtain averages over more extended periods so that short period errors would be minimized. Mean velocity vectors were, therefore, computed over periods of 10 to 12 minutes, the length of time being arbitrarily selected to fit the observations. This mean velocity was then assigned to a position and time at about the midpoint in the period. This long period averaging does not impose a greater restriction on the assumption of vertical movement noted above because it is the result of a summation of the shorter periods. Since only the gross features of the velocity field will be discussed, it is believed that the longer period average is acceptable. The results of the long period average of the observations are given in Table 4.3.

4.7 FINDINGS FROM OBSERVATIONS

Figures 4.8 and 4.8a are pictures of the cumulus cloud associated with the chaff tracer measurements of July 28, 1959. Figure 4.8 shows the cloud at 1055 MST about 10 minutes following the time of chaff drop. This time nearly coincides with the first period of average trajectory computations. Figure 4.8a shows the visible cloud at 1126 MST which is near the time of midpoint of the last trajectory computed. The two pictures, obtained from the photographic record of AFCRL, show the magnitude and vigor of the growth of the cumulus cloud
### TABLE 4.2
CHAFF TRAJECTORY DATA, JULY 26, 1959

<table>
<thead>
<tr>
<th>Elevation (ft MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>104\°31'</td>
</tr>
<tr>
<td>104\°33'</td>
</tr>
<tr>
<td>104\°35'</td>
</tr>
<tr>
<td>104\°37'</td>
</tr>
<tr>
<td>104\°41'</td>
</tr>
<tr>
<td>104\°45'</td>
</tr>
<tr>
<td>104\°51'</td>
</tr>
<tr>
<td>104\°57'</td>
</tr>
<tr>
<td>104\°63'</td>
</tr>
<tr>
<td>104\°69'</td>
</tr>
<tr>
<td>104\°75'</td>
</tr>
<tr>
<td>104\°81'</td>
</tr>
<tr>
<td>104\°87'</td>
</tr>
<tr>
<td>104\°93'</td>
</tr>
</tbody>
</table>

### Chart and Data

- **Time (18000)**
- **Range (17000)**
- **Arm Range (16000)**
- **Time Arm Range (15000)**
- **Arm Range (14000)**
- **Time Arm Range (13000)**
- **Arm Range (12000)**
- **Time Arm Range (11000)**
- **Arm Range (10000)**
- **Time Arm Range (9000)**
- **Arm Range (8000)**
- **Time Arm Range (7000)**
- **Arm Range (6000)**
- **Time Arm Range (5000)**
- **Arm Range (4000)**
- **Time Arm Range (3000)**
- **Arm Range (2000)**
- **Time Arm Range (1000)**
- **Arm Range (000)**

- **Chaff Parcel No. 1**

- **Time (18000)**
- **Arm Range (17000)**
- **Time Arm Range (16000)**
- **Time Arm Range (15000)**
- **Time Arm Range (14000)**
- **Time Arm Range (13000)**
- **Time Arm Range (12000)**
- **Time Arm Range (11000)**
- **Time Arm Range (10000)**
- **Time Arm Range (9000)**
- **Time Arm Range (8000)**
- **Time Arm Range (7000)**
- **Time Arm Range (6000)**
- **Time Arm Range (5000)**
- **Time Arm Range (4000)**
- **Time Arm Range (3000)**
- **Time Arm Range (1000)**
- **Time Arm Range (000)**
<table>
<thead>
<tr>
<th>Period</th>
<th>18,000 ft</th>
<th>16,000 ft</th>
<th>15,000 ft</th>
<th>14,000 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time</td>
<td>Range</td>
<td>dd/ff</td>
<td>Time</td>
</tr>
<tr>
<td>A</td>
<td>1050</td>
<td>10.5</td>
<td>11/10.8</td>
<td>1050</td>
</tr>
<tr>
<td>B</td>
<td>1101</td>
<td>9.3</td>
<td>19/9.7</td>
<td>1101</td>
</tr>
<tr>
<td>C</td>
<td>1114</td>
<td>7.5</td>
<td>14/7.7</td>
<td>1113</td>
</tr>
<tr>
<td>D</td>
<td>1124</td>
<td>6.4</td>
<td>01/8.9</td>
<td>1124</td>
</tr>
<tr>
<td>E</td>
<td>1134</td>
<td>5.9</td>
<td>15/15.6</td>
<td>1135</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Period</th>
<th>18,000 ft</th>
<th>16,000 ft</th>
<th>14,000 ft</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Time</td>
<td>Range</td>
<td>dd/ff</td>
</tr>
<tr>
<td>A</td>
<td>1051</td>
<td>12.2</td>
<td>41/5.4</td>
</tr>
<tr>
<td>B</td>
<td>1102</td>
<td>11.3</td>
<td>49/7.3</td>
</tr>
<tr>
<td>C</td>
<td>1114</td>
<td>9.9</td>
<td>04/7.4</td>
</tr>
<tr>
<td>D</td>
<td>1126</td>
<td>8.4</td>
<td>05/7.9</td>
</tr>
</tbody>
</table>
Figs. 4.8 and 4.8a. Cumulus cloud associated with chaff trajectory study.
during the period of observation. It will be observed that the cloud consisted of more than a single cell.

The first radar echo from the cloud was detected at 1102 MST at an altitude of 20,000 to 23,000 ft MSL. This echo grew rapidly and, by 1111 MST, it extended throughout the vertical extent of the cloud from 12,500 to over 25,000 ft. Figure 4.9 is a radar scope picture of the cloud taken at about 1111 MST showing the cloud at an elevation of about 16,000 ft MSL. The two chaff parcels, clearly defined at this level, are also shown. Figure 4.10 is a composite of the radar echoes from the cloud at four elevations for approximately the half hour of chaff trajectory observation. The character of the echo growth and movement will be referred to in a later section.

The trajectories of the two chaff parcels, reduced as described above, are plotted in Fig. 4.11 on a cartesian coordinate system with the radar as origin. The mean trajectory vectors are plotted to scale with the origin being located near the mean location for the period of averaging. The time indicated for each set of vectors is the approximate midpoint in the period of the average. An approximation is again involved in that vectors at all levels are shown to have a common origin. This was not the case in the later periods of observation since the vertical velocity shear had resulted in a displacement of the chaff in the upper levels relative to that at a lower elevation. The approximation implies some degree of spatial uniformity in the horizontal wind field and is made for convenience in plotting the data. The maximum area covered by the cloud radar echo during the period is shown as a shaded area for reference.

Surface wind measurements made at three locations in the vicinity of the developing cloud by personnel of the Atmospheric Research Group are shown for Fort Valley Experiment Station (FVS), MRI Radar Site, and Doyle Saddle. The range of wind directions observed during the period of chaff observations is indicated in Fig. 4.11 by an arc encompassing the extremes. Upper level wind measurements obtained from a radiosonde observation at the radar site at 1250 MST are also shown to an elevation of 23,000 ft MSL.

4.8 DISCUSSION

The observation of the motion of chaff parcels in the close proximity of a developing cumulus cloud offers some measure of the disturbance of the mean flow caused by a convective cell. If a model of the convective cloud such as that proposed by Newton and Newton is assumed, the chaff trajectories and radar observations may be employed to assess the suitability of the model.

The model proposed by Newton is shown in Fig. 4.12. This figure has been copied directly from the paper as published. A convective squall line existing in a mean flow having a horizontal velocity shear is illustrated. The vertical transport of horizontal momentum by the in-cloud vertical velocities results in in-cloud horizontal velocity differing from the free stream velocity at both
Fig. 4.9. Radar echoes from cloud and chaff parcels at 1111 MST, July 28, 1959.
Fig. 4.10. Composite of radar echoes for period of chaff trajectory measurements, 1100 to 1130, July 26, 1959.
Fig. 4.11. Trajectories of chaff parcels averaged over 10-minute periods for altitude and time indicated.
Fig. 4.12. Schematic cross section through squall line or large rainstorm. Lengths of horizontal arrows proportional to wind speeds outside cloud system. (Journal of Meteorology, Vol. 16, No. 5, October, 1959, p. 490.)
the upper and lower portion of the cloud. Horizontal convergence and divergence in the free stream must result as shown in the figure.

This model assumed a squall line of indefinite cross wind extent. However, Newton proposes that for an isolated cell the..." air might be imagined to divide and pass around the sides...without actual convergence and divergence." This would, in essence, imply a divergence of the streamlines around the cloud with subsequent convergence on the downstream side. The relative in-cloud and free stream velocities and induced pressure fields would be as shown in the model.

Evaluation of the in-cloud velocities from the observations of the cloud radar echo is difficult. Throughout the period from 1102 to 1123, no consistent movement can be detected. A gradual growth of the cloud towards the east and southeast is apparent. The lack of cloud movement as compared to the movement of the chaff parcels is a striking indication of the process proposed by Newton. Estimates of the movement of the center of the cloud radar echo at 20,000 and 13,000 ft have been made from the radar record. The estimated velocities are 325 degrees at 3.5 knots for the 20,000 ft level and 350 degrees at 3.0 knots for the 13,000 ft level. These estimates are very inaccurate because of the small movement and rapid development of the cloud echo.

Estimates of the environmental winds may be obtained from the chaff movement observed in proximity to the cloud. For this purpose, the movement of No. 1 chaff parcel for the first period was employed, since it was believed to be more representative of the undisturbed flow. The resulting vector diagram showing the estimated relative velocity between the undisturbed environment, and the cloud, is shown in Fig. 4.13. In this diagram \( V_{C0} \) represents the estimated cloud velocity at 20,000 ft, \( V_{C1} \) the cloud velocity at 13,000 ft, \( V_{u0} \) the environmental wind velocity at 18,000 ft, and \( V_{u1} \) the wind velocity at 15,000 ft. The resultant vectors, \( V_R \), which would give the direction of the hydrodynamic pressure gradients, have been entered as dashed lines because it is believed the accuracy of the estimated velocity vectors warrant only very limited confidence.

The development by Newton shows that for the condition that the mean horizontal velocity at a given level in a convective cloud remain unchanged with time, the following condition must apply.

\[
\frac{\partial C}{\partial Z} \approx \frac{4A \Delta \bar{w}_m}{\rho \pi D}
\]

where \( \bar{w}_m = \text{vertical velocity} \)

\( C = \text{average in-cloud velocity at a given level} \)
$V_{Cu} = 325°, 3.5$ Knots
$V_{Cl} = 350°, 3.0$ Knots
$V_{Eu} = 11°, 10.8$ Knots
$V_{El} = 09°, 8.7$ Knots

Fig. 4.13. Vector diagram showing estimated in-cloud and ambient velocities.
\( \overline{\mathcal{F}}_m \) = hydrodynamic pressure
\( \rho \) = air density
\( D \) = cloud diameter

and the subscript \( m \) implies horizontal averaging over the extent of the cloud.

It is further shown by Newton that for realistic Reynolds numbers, \( \overline{\mathcal{F}}_m \) is proportional to \( \rho V R^2 / 2 \) and the above relationship becomes:

\[
D \alpha = \frac{V_R^2}{w_m \partial C / \partial z}
\]

This relationship shows that for a given cloud diameter and given environmental wind relative to in-cloud wind, the vertical shear, \( \partial C / \partial z \), will be less for clouds having a large vertical velocity. The converse will also be true. Thus, clouds maintain a relatively vertical axis during active growth but the cirrus tops shear off due to a lack of vertical transport of horizontal momentum.

In the model by Newton, it is assumed that downdrafts within the cloud transport air having horizontal momentum greater than that of the environment into the lower levels of the cloud. A relative velocity opposite, or at least differing in direction, from that at the upper portion of the cloud results. This was not observed to apply to the cloud in which the chaff trajectories were measured near San Francisco Peaks, on July 28, 1959.

In this case, even the chaff at levels near the cloud base appeared to indicate an ambient velocity greater than that of the cloud radar echo. Thus, the relative velocity between ambient and in-cloud air showed only a small amount of shear between the 15,000 and 18,000 ft levels. It might be observed, however, that the cloud base was lower than 15,000 ft and the top higher than 18,000 ft so that observations at these levels do not represent actual conditions at either the base or at the top of the cloud. In actuality, the measurements represent the flow conditions more nearly at the midpoint of the cloud. The final periods of the chaff trajectory, in which measurement of the trajectory at 13,000 ft was possible, indicate that the flow at cloud base may have had a southerly component. The surface observations at Doyle Saddle substantiate this indication.

Thus, the relative velocity at the cloud base may have differed by a significant amount from that indicated in Fig. 4.13. If the surface winds at Doyle Saddle are taken as representative of the ambient wind near the cloud base, the relative velocity vector would then have a southerly component. This would result in a wind field more nearly in conformance to Newton's model and would also explain the ability of the cloud to remain nearly stationary relative to the ambient wind field at higher levels.
The analysis given by Newton may be followed somewhat further. If a velocity differential does exist between the cloud and the ambient wind field, then a hydrodynamic pressure field will be induced. The magnitude and direction of the hydrodynamic pressure will be determined by the magnitude and direction of the relative velocity vectors. Positive pressure will exist on the upwind relative velocity side of the cloud and negative pressure on the downwind side. Thus as shown by Newton, the hydrodynamic pressure field may produce a vertical pressure gradient independent of thermal stability if a direction shear in relative velocity exists between the upper and lower portions of the cloud. The growth of the cumulus cloud through development of new cells would be expected to proceed on the side of the cloud where the vertical pressure gradient due to hydrodynamical forces is directed upward.

In the present case, it is not possible to assign an accurate estimate to the magnitude of the velocities near the cloud base. However, it is interesting qualitatively to note the relationships observed. If it is assumed, as was done above, that the relative velocity vector near the cloud base has a southerly direction while that near the cloud top has a northerly direction, the resulting vertical pressure gradient will be positive upward on the south side of the cloud. This pressure gradient should result in increased instability and continued growth of the cloud on the south side of the original cloud. It may be observed from the composite diagram of the cloud radar echoes shown in Fig. 4.10 that the cloud development did actually occur on the south and southeast side of the original cloud. It is difficult to place much confidence in this observation since the estimation of the relative wind vectors at low levels is very uncertain.

4.9 SUMMARY

The use of "chaff" as a tracer of air movement in the proximity of a developing cumulus cloud near the San Francisco Peaks on July 28, 1959 has provided evidence of the feasibility of the technique to study the velocity field near such clouds. The limited data available from the single case offer evidence that a cloud model such as that proposed by Newton14 may be appropriate. While precise analysis of the wind field is not possible from the data available, a definite indication of convergence of the streamlines in the downstream direction from the cloud was observed. The hydrodynamic pressure field induced by the indicated relative velocity between in-cloud and ambient winds predicts development of the cloud in a direction supported by observed development.

The possibility of a completely fortuitous coincidence of events giving the results observed here cannot be overlooked. The cloud development occurred near the San Francisco Peaks which extend to an altitude of about 12,000 ft MSL. The peaks, therefore, must have a pronounced influence on the wind field to some height above the summit. It is, therefore, not possible to separate the influence of the peaks upon the wind field from that of the cumulus cloud. It would
be desirable and appropriate to duplicate measurements such as reported here in an environment of more uniform terrain. Substantial reliance can be placed upon the present observations only after observations are made to substantiate or refute the results reported here.

4.10 RECOMMENDATIONS FOR FUTURE OBSERVATIONS

It is believed that the observations reported here represent sufficient evidence that the application of tracer techniques can reveal more detail of the flow characteristics near cumulus clouds than have been previously observed. However, the use of chaff is limited by the restriction that the radar echo from the chaff cannot be distinguished from that due to precipitation with the desired degree of confidence. This restriction limits observations within the cloud to periods prior to development of the precipitation echo. Observations of chaff not originally dispersed within a cloud may even be subject to doubt unless visual photographs are available to verify the boundaries of the cloud. The use of chaff is, therefore, limited to a rather restricted type of measurement and may not be expected to yield results of significantly greater accuracy than herein reported.

An approach that would appear to offer potential of obtaining more accurate trajectory information would be that employed by Angell and Pack. Small, constant volume, super-pressured balloons were employed as Lagrangian tracers. The balloons attain and remain at an equilibrium pressure altitude unless subjected to a vertical displacement force by vertical air movement. Because the restoring forces are small, the balloons respond essentially to the vertical air velocities unless displaced a large distance from the equilibrium level. Balloons launched upwind from a cumulus cloud should either be entrained into the cloud or follow the streamlines around the cloud and thus indicate the character of air flow as desired.

Tracking of the balloons could be accomplished by an automatic tracking radar as employed by Angell and Pack. Since this would require a special radar and would then permit tracking of only a single balloon, a method using a transponder such as that described by Dickson and Pound would seem advantageous. Use of transponders would permit tracking several balloons simultaneously by a single PPI radar while the same radar was being employed to observe the precipitation echo from the cloud under study.

The transponder is designed to "answer" on a frequency different from that of the radar so that tracking should be possible even within a dense precipitation echo area. Limitation for in-cloud measurements would result from the effects of precipitation of icing on the free lift of the balloon. However, even in the event of moderate icing, a semi-quantitative measure of in-cloud velocities could be obtained.

Although difficulty would be experienced in launching balloons to attain
the desired altitude and position relative to a developing cumulus cloud, it is believed that this technique offers a possibility to obtain a more accurate quantitative measure of the wind field near the cloud than that obtained by use of chaff. The single advantage of chaff as a tracer agent is the property of vertical diffusion which makes possible trajectory measurement at several altitudes. Either technique possesses potential to yield valuable information and should be employed in some future program of cloud dynamics study.
CHAPTER 5

PROJECT HI-CUE 1961 OBSERVATIONS

5.1 INTRODUCTION

In the summer of 1961 equipment and staff were sent to Flagstaff, Arizona, to join with others in the Project Hi-Cue field program. The University of Michigan group maintained two primary activities: (1) the AN/APQ-40 van-mounted radar unit was operated from its station at Flagstaff Municipal Airport, and (2) the photoelectric raindrop-size spectrometer was operated at the Walter Kent Ranch, northwest of Flagstaff and southwest of Mt. Agassiz. The group at the Kent Ranch also undertook to make two-theodolite pilot balloon soundings to determine some of the characteristics of the air movement below the cloud bases.

We were particularly gratified, and our effort was greatly aided by the generosity of Mr. Walter Kent and his family in allowing us to establish our station on their land, to connect to their service box for our electric power, and to erect temporary power lines and other structures necessary for our work.

The cooperation of our colleagues in the Hi-Cue program also deserves special mention. Each of the participating groups contributed to our operation in one or more ways, and the Kent Ranch site became the most comprehensively instrumented field station in the study area. The municipal airport was, of course, the seat of all the radar operations, the GRD radiosonde station, the T-11 stereocamera setup, and the base for the flying cloud physics laboratories.

5.2 OBSERVATIONS TAKEN AT THE KENT RANCH STATION

As early as 14 July, when the installation of the raindrop-size spectrometer was not yet completed, a moderate shower of small hail occurred at the station. Precipitation did not again occur until 20 July. From this date through August 4, data were collected in all rains. The log of raindrop-size data is presented in Table 5.1.

Two-theodolite balloon sounding equipment was obtained and a baseline established by 21 July, and soundings were made as appropriate through 3 August. The log of these soundings is presented in Table 5.2.

5.3 RADAR OBSERVATIONS

The APQ-40 radar was operated at Flagstaff Municipal Airport in support of Project Hi-Cue during July and August, 1961. Observations were coordi-
TABLE 5.1

SUMMARY AND EVALUATION OF RAINDROP-SIZE SPECTROMETER DATA

Walter Kent Ranch
Flagstaff, Arizona
July 1961 - August 1961

<table>
<thead>
<tr>
<th>Date</th>
<th>Times</th>
<th>Precip. Amount (Inch)</th>
<th>Spectrometer Data</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 14</td>
<td>1050-1105</td>
<td>.100</td>
<td>Spectrometer not installed</td>
<td>Precip. in the form of hail. 1050-1105.</td>
</tr>
<tr>
<td></td>
<td>1105-1145</td>
<td>.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-19</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2245-2315</td>
<td>.025</td>
<td>Fair data</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1450-1515</td>
<td>.055</td>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1155-1210</td>
<td>.005</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1145-1225</td>
<td>.275</td>
<td>Fair to good</td>
<td>Precip. Mainly hail, so spectrometer data is not calibrated.</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1420-1530</td>
<td>.075</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>1250-1325</td>
<td>.040</td>
<td>Fair to good</td>
<td>Small variation in gain to the oscillograph.</td>
</tr>
<tr>
<td>28</td>
<td>1230</td>
<td>T</td>
<td></td>
<td>Data requires a careful analysis.</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>0</td>
<td></td>
<td>Data complete for entire rain.</td>
</tr>
<tr>
<td>30</td>
<td>1452-1603</td>
<td>.570</td>
<td>Fair to good</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>1057-1450</td>
<td>.340</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Aug. 1</td>
<td>1432-1605</td>
<td>.455</td>
<td>Fair</td>
<td>Some sections of storm not recorded and a few sections not reliable.</td>
</tr>
<tr>
<td>2</td>
<td>1202-1245</td>
<td>.090</td>
<td>No record</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2230-0130</td>
<td>.015</td>
<td>No record</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1420-1500</td>
<td>.085</td>
<td>Fair</td>
<td>Power failure due to lightning resulted in some missing data and lack of warm-up time gave variable gain.</td>
</tr>
<tr>
<td></td>
<td>1528-2045</td>
<td>.310</td>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1215-1435</td>
<td>.440</td>
<td>Fair</td>
<td>Slight change in gain during the storm. Last 0.10 in. of rain not recorded.</td>
</tr>
<tr>
<td>5</td>
<td>1945-2200</td>
<td>.635</td>
<td>No record</td>
<td>Spectrometer dismantled.</td>
</tr>
</tbody>
</table>

The above is a complete record of all the rainfall which occurred at Kent's Ranch during the operational period.
### Table 5.2

**Two-Theodolite Pilot Balloon Soundings**

**Walter Kent Ranch**  
**Flagstaff, Arizona**  
**July 1961 - August 1961**

<table>
<thead>
<tr>
<th>Date</th>
<th>Release Time</th>
<th>Duration of Flight (Min)</th>
<th>Approximate Free Lift (GM)</th>
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</thead>
<tbody>
<tr>
<td>July 21</td>
<td>1612</td>
<td>13</td>
<td>35</td>
</tr>
<tr>
<td>22</td>
<td>1019</td>
<td>22</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>1102</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>1345</td>
<td>24</td>
<td>50</td>
</tr>
<tr>
<td>23</td>
<td>1000</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td>8.5</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>1211</td>
<td>32.5</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>1447</td>
<td>23</td>
<td>45</td>
</tr>
<tr>
<td>25</td>
<td>0907</td>
<td>56</td>
<td>40</td>
</tr>
<tr>
<td>26</td>
<td>0919</td>
<td>17</td>
<td>65</td>
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nated with measurements by an AN/APQ-70 radar operated by the AFRL and with a raindrop-size spectrometer operated by The University of Michigan. However, equipment malfunctions severely limited the periods of successful quantitative data collection.

Modification of the radar antenna control system prior to the program permitted relatively rapid data acquisition while operating in the RHI mode. A large portion of the measurements were made in RHI mode to facilitate more frequent measures of the cloud reflectivity over the drop-size spectrometer site. Only a small azimuth sector was usually scanned on either side of the spectrometer site. While this practice neglected observation of cloud development at other azimuths, it permitted a much greater time resolution in measurements of cloud reflectivity over the spectrometer site.

Calibration of the radar by measurement of power return from a spherical target was accomplished on two occasions. A one meter diameter Suchy Target Balloon (Suchy Division, Inc., New York) was tethered at an elevation of about 1000 ft at a range of one mile. A single measurement of power returned from this spherical target indicated an antenna gain 4 db less than that computed from geometrical dimensions. A series of measurements of power returned from a 6" diameter spun aluminum sphere indicated the same antenna gain within a fraction of a decibel. It was, therefore, possible to convert the radar measurements to reflectivity units with an accuracy equal to that of the test set employed.

A log of radar measurements made during the period July 17 through August 5, 1961 is included in Table 5.3. The RHI data are logged together with the azimuth or range of azimuth covered by the observations. In general, all RHI data are gain series measurements at 2 degrees increments of azimuth. PPI data are of two types; gain series and either fixed elevation time-lapse or elevation series. The gain and elevation PPI data are logged separately and the range of most frequent data are entered. All time entries are Mountain Standard Time.

5.4 REDUCTION AND PRESENTATION OF DATA

Pursuant to an agreement among participants, reached in conference, data reduction and analysis has been done mainly for observations taken on 27 and 31 July and 1 August.

The recording oscillograph charts for these dates were reduced to punched card records of the raindrop-size spectra, and these were processed by electronic computer (IBM 709) to give the various familiar rainfall and radar parameters. The results of these computations are presented in Table 5.4.

The computed values probably do not warrant any greater accuracy than three significant figures for any quantity printed. A greater number of fig-
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<td></td>
<td></td>
<td>1412-1445</td>
<td>20 (100)</td>
</tr>
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<td></td>
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<td></td>
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<td>1040-1054</td>
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<td></td>
<td>1107-1113</td>
<td>20</td>
</tr>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
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<td></td>
<td>1258-1300</td>
<td>20</td>
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<tr>
<td>Table 5.4</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>COMPUTER OUTPUT OF DATA ON AND PARAMETERS DERIVED FROM RAINDROP-SIZE SPECTRA</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Walter Kent Ranch</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Flagstaff, Arizona</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>July 27, 31, and August 1, 1961</td>
<td></td>
<td></td>
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<tr>
<td>RAINDROP-SIZE DISTRIBUTION DATA FOR 7-27-1961</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOTE: NUMBER OF DROPS GIVEN IN NUMBER PER CUBIC METER PER MM STARTING AT 0.6 MM AND IN 0.2 MM CLASSES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| STARTING TIME | LENGTH OF SAMPLE | NUMBER OF DROPS | | | |
|---------------|-----------------|-----------------|----|----|----|----|----|----|----|----|----|----|
| 1221.00       | 60              | 18.350          | 11.949 | 5.549 | 13.039 | .000 | 6.294 | .000 | .000 | 6.626 | .000 |
| 1222.00       | 60              | 12.447          | 6.047  | 6.047 | 6.116 | .000 | .000  | .000 | .000 | .000 | 7.744 |
| 1223.00       | 60              | 31.658          | 11.424 | .000  | .000  | .000  | .000  | .000 | .000 | 6.625 | .000 |
| 1241.30       | 30              | 88.948          | 60.546 | 21.658 | .000  | .000  | .000  | .000  | .000 | 15.090 | 15.771 |
| 1242.00       | 60              | 76.632          | 90.233 | 5.541 | 4.180 | 6.494 | 5.724 | .000 | .000 | 6.988 | .000 |
| 1243.00       | 60              | 17.459          | 5.588  | 11.429 | 20.373 | 6.559 | 21.947 |
| 1244.00       | 60              | 17.459          | 5.588  | 11.429 | 20.373 | 6.559 | 21.947 |

Z = 2792500E-04 M4&H4=3 M = .49313E-01 GM PER CUBIC METER DZERO = 3.330MM |
| PRECIP INTENSITY = 1.368 MM PER HOUR ATTENUATION = 61933E-01 DB PER KM G = .012 |
| Z = 1613500E-03 M4&H4=3 M = .10981E-01 GM PER CUBIC METER DZERO = 3.136MM |
| PRECIP INTENSITY = .247 MM PER HOUR ATTENUATION = .31352E-02 DB PER KM G = .085 |
| Z = 1312500E-03 M4&H4=3 M = .10664E-01 GM PER CUBIC METER DZERO = 1.916MM |
| PRECIP INTENSITY = .223 MM PER HOUR ATTENUATION = .22520E-02 DB PER KM G = .847 |
| Z = 9572500E-03 M4&H4=3 M = .46646E-01 GM PER CUBIC METER DZERO = 2.197MM |
| PRECIP INTENSITY = 1.098 MM PER HOUR ATTENUATION = .16127E-01 DB PER KM G = 1.008 |
| Z = 1875700E-04 M4&H4=3 M = .54549E-01 GM PER CUBIC METER DZERO = 2.573MM |
| PRECIP INTENSITY = 1.405 MM PER HOUR ATTENUATION = .34523E-01 DB PER KM G = 1.057 |
| Z = 903800E-02 M4&H4=3 M = .16851E-01 GM PER CUBIC METER DZERO = 1.510MM |
| PRECIP INTENSITY = .312 MM PER HOUR ATTENUATION = .22186E-02 DB PER KM G = .887 |

---

**Note:** The table above contains detailed data on raindrop-size distribution, including the number of drops at various starting times, lengths of samples, and corresponding precipitation intensity, attenuation, and zero values in millimeters (mm) and decibels (dB) per kilometer (km), along with their respective parameters.
<table>
<thead>
<tr>
<th>Starting Time</th>
<th>Length of Sample</th>
<th>Number of Drops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1244.00</td>
<td>60</td>
<td>12.37A 000 6.187 7.040</td>
</tr>
<tr>
<td>1245.00</td>
<td>60</td>
<td>18.581 11.521 -000 21.121</td>
</tr>
<tr>
<td>1246.00</td>
<td>60</td>
<td>19.201 6.400 19.201</td>
</tr>
<tr>
<td>1247.00</td>
<td>60</td>
<td>18.458 18.458 6.960 -000 7.436</td>
</tr>
<tr>
<td>1248.00</td>
<td>60</td>
<td>12.587 12.587 7.040</td>
</tr>
<tr>
<td>1249.00</td>
<td>60</td>
<td>18.284 18.284 4.459 -000 6.730 7.055 7.375 7.116</td>
</tr>
<tr>
<td>1250.00</td>
<td>60</td>
<td>\text{Number of Drops}</td>
</tr>
<tr>
<td>Time</td>
<td>Length of Sample</td>
<td>Number of Drops</td>
</tr>
<tr>
<td>--------</td>
<td>------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>1251.00</td>
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<td>87.487</td>
</tr>
<tr>
<td>1252.00</td>
<td>60</td>
<td>255.019</td>
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<td>56.946</td>
</tr>
<tr>
<td>1254.00</td>
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<td>5.599</td>
</tr>
<tr>
<td>1256.00</td>
<td>60</td>
<td>5.974</td>
</tr>
<tr>
<td>STARTING TIME</td>
<td>LENGTH OF SAMPLE</td>
<td>NUMBER OF DROPS</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>1257.00</td>
<td>60</td>
<td>-0.00</td>
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<tr>
<td>1306.00</td>
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<td>1307.00</td>
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<td>60.726</td>
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<td>1308.00</td>
<td>60</td>
<td>167.669</td>
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<td>1309.00</td>
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<td>231.111</td>
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<td>1310.00</td>
<td>60</td>
<td>193.321</td>
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<tr>
<td>1311.00</td>
<td>60</td>
<td>8.1375</td>
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</tbody>
</table>

**Notes:**
- Z values are calculated using the formula: \(Z = \frac{M}{M_{0}} - 1\)
- M values are estimated using the relationship: \(M = \frac{b}{y} \times 10^{x}\)
- UZERU values are determined based on Z and M values.
<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
<th>NUMBER OF DROPS</th>
<th>MEAN DROP SIZE</th>
<th>MEAN DROP DENSITY</th>
<th>MEAN DROP VOLUME</th>
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</thead>
<tbody>
<tr>
<td>1312.00</td>
<td>60</td>
<td>155.82</td>
<td>50.00</td>
<td>8.03</td>
<td>1.59</td>
</tr>
<tr>
<td>1313.00</td>
<td>60</td>
<td>130.43</td>
<td>75.00</td>
<td>6.16</td>
<td>1.17</td>
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<tr>
<td>1313.00</td>
<td>60</td>
<td>130.43</td>
<td>75.00</td>
<td>6.16</td>
<td>1.17</td>
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<td>1314.00</td>
<td>60</td>
<td>132.23</td>
<td>79.00</td>
<td>4.24</td>
<td>0.87</td>
</tr>
<tr>
<td>1315.00</td>
<td>60</td>
<td>132.23</td>
<td>79.00</td>
<td>4.24</td>
<td>0.87</td>
</tr>
<tr>
<td>1316.00</td>
<td>60</td>
<td>130.43</td>
<td>75.00</td>
<td>6.16</td>
<td>1.17</td>
</tr>
<tr>
<td>1317.00</td>
<td>60</td>
<td>132.23</td>
<td>79.00</td>
<td>4.24</td>
<td>0.87</td>
</tr>
<tr>
<td>Start Time</td>
<td>Length of Sample</td>
<td>Number of Drops</td>
<td>Precipitation Intensity</td>
<td>Attenuation</td>
<td>Zeros</td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
<td>-----------------</td>
<td>-------------------------</td>
<td>-------------</td>
<td>--------</td>
</tr>
<tr>
<td>1316.00</td>
<td>60</td>
<td>110.457</td>
<td>46.453 60.143 26.210 50.104 13.936 0.000 15.098 7.685</td>
<td>Z = 1.4761E-04 MM/H-M-3  M = 1.0000E 00 GM PER CUBIC METER  ZEROS = 1.711MM</td>
<td>PRCIP INTENSITY = 2.163 MM PER HOUR  ATTENUATION = 2.636E-01 DB PER KM</td>
</tr>
<tr>
<td>1320.00</td>
<td>60</td>
<td>163.433</td>
<td>61.027 22.624 40.311 27.556 6.340 21.980 7.398 7.144</td>
<td>Z = 5.1593E-03 MM/H-M-3  M = 3.5530E-01 GM PER CUBIC METER  ZEROS = 1.764MM</td>
<td>PRCIP INTENSITY = 1.084 MM PER HOUR  ATTENUATION = 0.984E-02 DB PER KM</td>
</tr>
<tr>
<td>1321.00</td>
<td>60</td>
<td>66.913 66.913</td>
<td>15.710 90.709 13.939 14.631</td>
<td>Z = 1.3153E-03 MM/H-M-3  M = 3.0442E-01 GM PER CUBIC METER  ZEROS = 1.161MM</td>
<td>PRCIP INTENSITY = 0.556 MM PER HOUR  ATTENUATION = 0.358E-02 DB PER KM</td>
</tr>
<tr>
<td>1322.00</td>
<td>60</td>
<td>37.404 50.204</td>
<td>15.806 20.713 6.970 7.316</td>
<td>Z = 6.5559E-02 MM/H-M-3  M = 2.0365E-01 GM PER CUBIC METER  ZEROS = 0.964MM</td>
<td>PRCIP INTENSITY = 0.318 MM PER HOUR  ATTENUATION = 0.201E-02 DB PER KM</td>
</tr>
<tr>
<td>1323.00</td>
<td>60</td>
<td>83.205 66.004</td>
<td>39.322 48.432</td>
<td>Z = 1.1813E-02 MM/H-M-3  M = 3.3353E-02 GM PER CUBIC METER  ZEROS = 0.761MM</td>
<td>PRCIP INTENSITY = 0.115 MM PER HOUR  ATTENUATION = 0.6970E-03 DB PER KM</td>
</tr>
<tr>
<td>Starting Time</td>
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<td>Number of Drops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>------------------</td>
<td>-----------------</td>
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<td></td>
</tr>
<tr>
<td>1324.00</td>
<td>60</td>
<td>70.405</td>
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</tr>
<tr>
<td>1325.00</td>
<td>60</td>
<td>25.602</td>
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<tr>
<td>1326.00</td>
<td>60</td>
<td>19.201</td>
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<tr>
<td>1327.00</td>
<td>60</td>
<td>12.801</td>
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<tr>
<td>1521.30</td>
<td>30</td>
<td>11.202</td>
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</tr>
<tr>
<td>1522.00</td>
<td>60</td>
<td>5.412</td>
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</tr>
<tr>
<td>1523.00</td>
<td>60</td>
<td>1.625</td>
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</tbody>
</table>

Starting Time: 1324.00
Length of Sample: 60
Number of Drops: 70.405

Z: 0.1328E+01 MM M-3
M: 0.7420E-02 GM PER CUBIC METER
DZERO: 0.552MM

Precip Intensity = 0.002 CM PER HOUR
Attenuation = 1.1461E-02 DB PER KM
G = 1.634

Starting Time: 1325.00
Length of Sample: 60
Number of Drops: 25.602

Z: 0.9108E-03 MM M-3
M: 0.1274E-02 GM PER CUBIC METER
DZERO: 0.708MM

Precip Intensity = 0.013 MM PER HOUR
Attenuation = 0.8539E-04 DB PER KM
G = 1.062

Starting Time: 1326.00
Length of Sample: 60
Number of Drops: 19.201

Z: 0.8503E+00 MM M-3
M: 0.1127E-02 GM PER CUBIC METER
DZERO: 0.718MM

Precip Intensity = 0.012 CM PER HOUR
Attenuation = 0.7633E-04 DB PER KM
G = 1.072

Starting Time: 1327.00
Length of Sample: 60
Number of Drops: 12.801

Z: 0.1144E+00 MM M-3
M: 0.2895E-03 GM PER CUBIC METER
DZERO: 0.550MM

Precip Intensity = 0.003 MM PER HOUR
Attenuation = 0.1012E-04 DB PER KM
G = 1.290

Starting Time: 1521.30
Length of Sample: 30
Number of Drops: 11.202

Z: 0.1025E+03 MM M-3
M: 0.1349E-01 GM PER CUBIC METER
DZERO: 1.358MM

Precip Intensity = 0.349 MM PER HOUR
Attenuation = 0.2407E-02 DB PER KM
G = 1.108

Starting Time: 1522.00
Length of Sample: 60
Number of Drops: 5.412

Z: 0.4611E+02 MM M-3
M: 0.1262E-01 GM PER CUBIC METER
DZERO: 1.114MM

Precip Intensity = 0.207 MM PER HOUR
Attenuation = 0.1304E-02 DB PER KM
G = 1.122

Starting Time: 1523.00
Length of Sample: 60
Number of Drops: 1.625

Z: 0.5611E+02 MM M-3
M: 0.1126E-01 GM PER CUBIC METER
DZERO: 1.333MM

Precip Intensity = 0.202 MM PER HOUR
Attenuation = 0.1359E-02 DB PER KM
G = 1.093
<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1524.00</td>
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**NUMBER OF DROPS**

<table>
<thead>
<tr>
<th>25.201</th>
<th>6.000</th>
<th>6.350</th>
<th>6.827</th>
<th>7.175</th>
</tr>
</thead>
</table>

**Z = 16620E-02 MMAM-3**

**M = 4.207E-02 GM PER CUBIC METER**

**DZERO = 1.173MM**

**PRECIP INTENSITY = 0.077 MM PER HOUR**

**ATTENUATION = 0.5824E-03 UP PER KM**

**G = 1.123**

<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1525.00</td>
<td>60</td>
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</tbody>
</table>

**NUMBER OF DROPS**

<table>
<thead>
<tr>
<th>31.386</th>
<th>11.573</th>
<th>0.000</th>
<th>13.866</th>
<th>7.175</th>
</tr>
</thead>
</table>

**Z = 1994E-02 MMAM-3**

**M = 5.9017E-02 GM PER CUBIC METER**

**DZERO = 1.165MM**

**PRECIP INTENSITY = 0.094 MM PER HOUR**

**ATTENUATION = 0.5886E-03 UP PER KM**

**G = 1.123**

<table>
<thead>
<tr>
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<th>LENGTH OF SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1526.00</td>
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</tbody>
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**NUMBER OF DROPS**

<table>
<thead>
<tr>
<th>95.366</th>
<th>17.921</th>
<th>0.000</th>
<th>21.121</th>
<th>7.175</th>
</tr>
</thead>
</table>

**Z = 14443E-02 MMAM-3**

**M = 6.940DE-02 GM PER CUBIC METER**

**DZERO = 1.169MM**

**PRECIP INTENSITY = 0.094 MM PER HOUR**

**ATTENUATION = 0.5792E-03 UP PER KM**

**G = 0.798**

<table>
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<tr>
<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
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<tbody>
<tr>
<td>1527.00</td>
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**NUMBER OF DROPS**

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<th>61.429</th>
<th>62.427</th>
<th>36.026</th>
<th>34.622</th>
<th>6.789</th>
<th>6.775</th>
<th>0.000</th>
<th>7.597</th>
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</table>

**Z = 1627E-03 MMAM-3**

**M = 2.6601E-01 GM PER CUBIC METER**

**DZERO = 1.168MM**

**PRECIP INTENSITY = 0.462 MM PER HOUR**

**ATTENUATION = 0.3694E-02 UP PER KM**

**G = 2.012**

<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
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</thead>
<tbody>
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</tbody>
</table>

**NUMBER OF DROPS**

<table>
<thead>
<tr>
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<th>43.740</th>
<th>10.939</th>
<th>12.582</th>
<th>0.000</th>
<th>13.667</th>
<th>0.000</th>
<th>7.398</th>
<th>7.744</th>
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</table>

**Z = 33360E-03 MMAM-3**

**M = 3.0501E-01 GM PER CUBIC METER**

**DZERO = 1.593MM**

**PRECIP INTENSITY = 0.609 MM PER HOUR**

**ATTENUATION = 0.6297E-02 UP PER KM**

**G = 1.417**

<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
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</thead>
<tbody>
<tr>
<td>1529.00</td>
<td>60</td>
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</tbody>
</table>

**NUMBER OF DROPS**

<table>
<thead>
<tr>
<th>43.228</th>
<th>62.629</th>
<th>49.629</th>
<th>27.341</th>
<th>21.130</th>
<th>0.000</th>
<th>7.456</th>
</tr>
</thead>
</table>

**Z = 11247E-03 MMAM-3**

**M = 2.5095E-01 GM PER CUBIC METER**

**DZERO = 1.161MM**

**PRECIP INTENSITY = 0.419 MM PER HOUR**

**ATTENUATION = 0.2818E-02 UP PER KM**

**G = 1.499**

<table>
<thead>
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<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1530.00</td>
<td>60</td>
</tr>
</tbody>
</table>

**NUMBER OF DROPS**

<table>
<thead>
<tr>
<th>43.128</th>
<th>43.429</th>
<th>49.629</th>
<th>27.341</th>
<th>21.130</th>
<th>0.000</th>
<th>7.456</th>
<th>7.456</th>
</tr>
</thead>
</table>

**Z = 11247E-03 MMAM-3**

**M = 2.5095E-01 GM PER CUBIC METER**

**DZERO = 1.161MM**

**PRECIP INTENSITY = 0.419 MM PER HOUR**

**ATTENUATION = 0.2818E-02 UP PER KM**

**G = 1.499**
<table>
<thead>
<tr>
<th>Time</th>
<th>Starting Time</th>
<th>Length of Sample</th>
<th>Number of Drops</th>
<th>Z</th>
<th>M</th>
<th>Dzero</th>
<th>Precip Intensity</th>
<th>Attenuation</th>
<th>G</th>
</tr>
</thead>
<tbody>
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<td>1531.00</td>
<td>1531.00</td>
<td>60</td>
<td>27.50</td>
<td>100.352</td>
<td>23.547</td>
<td>48.644</td>
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| NUMBER OF DROPS      |                     |
| 31.789               | 38.189               |
| 31.789               | 7.040               |
| Z = 1.2801E 02 MM4M-3 |
| M = 7.3695E-02 GM PER CUBIC METER |
| 0.100 MM PER HOUR    |
| ATTENUATION = 0.5931E-03 DB PER KM |
| G = 1.143            |
| COEF = 596.419220    |
| SL = 1.468868        |
| STER = 0.323017      |
| RPOS = 1.156045      |
| RNEG = -0.525638     |
| STERA = 0.334542     |
| COEFM = 0.048180     |
| SLM = 0.870211       |
| COEFD = 1.763768     |
| SLD = 0.194058       |
**RAINDROP-SIZE DISTRIBUTION DATA FOR 1-1-1961**

**NOTE.** NUMBER OF DROPS GIVEN IN NUMBER PER CUBIC METER PER MM STARTING AT 0.6 MM AND IN 0.2 MM CLASSES

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<th>STARTING TIME</th>
<th>LENGTH OF SAMPLE</th>
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<td>1430.00</td>
<td>60</td>
<td>21.589 22.997 15.074 9.000 6.000 3.000 7.673</td>
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<td>( Z = 2.926 \times 10^5 ) MM-3 ( M = 1.072 \times 10^{-2} ) MM PER CUBIC METER ( D \text{ZERO} = 1.924 ) MM ( G = 0.175 )</td>
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<td>PRECIP INTENSITY = 0.192 MM PER HOUR ( \text{ATTENUATION} = 1.1962 \times 10^{-2} ) DB PER KM ( G = 0.175 )</td>
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<td>1431.00</td>
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<td>15.997 15.897 9.536 6.656 8.316 8.888 4.000 9.681</td>
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<td>( Z = 2.965 \times 10^5 ) MM-3 ( M = 1.779 \times 10^{-2} ) MM PER CUBIC METER ( D \text{ZERO} = 2.118 ) MM</td>
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<td>PRECIP INTENSITY = 0.392 MM PER HOUR ( \text{ATTENUATION} = 1.3907 \times 10^{-2} ) DB PER KM ( G = 0.795 )</td>
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<tr>
<td>1432.00</td>
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<td>4.391 4.671 9.536 8.930 0.000 1.092 6.886 9.117 3.782</td>
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<td>( Z = 2.223 \times 10^5 ) MM-3 ( M = 6.794 \times 10^{-2} ) MM PER CUBIC METER ( D \text{ZERO} = 2.709 ) MM</td>
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<td>PRECIP INTENSITY = 1.797 MM PER HOUR ( \text{ATTENUATION} = 3.864 \times 10^{-2} ) DB PER KM ( G = 0.851 )</td>
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<tr>
<td>1433.00</td>
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<td>74.469 79.589 56.228 49.781 41.734 57.060 11.192 27.797 66.320 18.564</td>
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<td>( Z = 2.944 \times 10^5 ) MM-3 ( M = 2.777 \times 10^{-1} ) MM PER CUBIC METER ( D \text{ZERO} = 2.169 ) MM</td>
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<td>PRECIP INTENSITY = 6.810 MM PER HOUR ( \text{ATTENUATION} = 1.369 \times 10^{-2} ) DB PER KM ( G = 1.359 )</td>
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<td>( Z = 1.479 \times 10^5 ) MM-3 ( M = 4.890 \times 10^{-2} ) MM PER CUBIC METER ( D \text{ZERO} = 1.932 ) MM</td>
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<td>PRECIP INTENSITY = 20.645 MM PER HOUR ( \text{ATTENUATION} = 1.424 \times 10^{-2} ) DB PER KM ( G = 1.449 )</td>
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PRECIPE INTENSITY = 24.566 MM PER HOUR  
ATTENUATION = .36592E 00 DB PER KM  G = 1.279

STARTING TIME 1436.00  
LENGTH OF SAMPLE  60

NUMBER OF DROPS
2253.913  1342.534  1017.390  841.967  590.609  331.229  295.249  96.644  157.334  67.182
51.199  82.837  42.360

Z =  .29402E 05 kg/m^3  M = .15922E 01 g/m per cubic meter  DZERG = 1.779MM
PRECIPE INTENSITY =  35.076 MM PER HOUR  
ATTENUATION = .38395E 00 DB PER KM  G = 1.718

STARTING TIME 1437.00  
LENGTH OF SAMPLE  60

NUMBER OF DROPS
2067.028  2204.179  1573.282  1009.941  634.317  778.774  374.790  297.564  375.133  173.524
124.795  93.370  43.805  11.179  .056

Z =  .52141E 05 kg/m^3  M = .27915E 01 g/m per cubic meter  DZERG = 1.955MM
PRECIPE INTENSITY =  62.534 MM PER HOUR  
ATTENUATION = .29807E 00 DB PER KM  G = 1.308

STARTING TIME 1438.00  
LENGTH OF SAMPLE  60

NUMBER OF DROPS
2242.441  2390.143  1068.253  1307.793  1146.892  1084.795  992.122  412.937  462.876  223.510
102.046  107.559  32.608  45.737  1.771

Z =  .69431E 05 kg/m^3  M = .38779E 01 g/m per cubic meter  DZERG = 1.740MM
PRECIPE INTENSITY =  86.450 MM PER HOUR  
ATTENUATION = .12856E 01 DB PER KM  G = 1.635

STARTING TIME 1439.00  
LENGTH OF SAMPLE  36

NUMBER OF DROPS
2471.219  2639.372  1684.076  1292.620  1153.502  724.146  312.677  253.271  97.712  45.256
30.467

Z =  .15336E 05 kg/m^3  M = .18446E 01 g/m per cubic meter  DZERG = 1.395MM
PRECIPE INTENSITY =  35.153 MM PER HOUR  
ATTENUATION = .30833E 00 DB PER KM  G = 1.604

STARTING TIME 1440.00  
LENGTH OF SAMPLE  20

NUMBER OF DROPS
2582.213  1967.774  1438.369  1452.603  816.239  508.181  378.167  201.854  103.943  23.994
122.474  1580.62E 01 g/m per cubic meter  DZERG = 1.391MM
PRECIPE INTENSITY =  29.939 MM PER HOUR  
ATTENUATION = .25550E 00 DB PER KM  G = 1.557

STARTING TIME 1441.00  
LENGTH OF SAMPLE  60

NUMBER OF DROPS
2653.723  1583.185  705.136  405.148  291.535  152.375  111.651  83.056  20.777  29.700
1.220  4.220  3.155

Z =  .56398E 04 kg/m^3  M = .67049E 00 g/m per cubic meter  DZERG = 1.346MM
PRECIPE INTENSITY =  12.156 MM PER HOUR  
ATTENUATION = .11491E 00 DB PER KM  G = 1.804
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<tr>
<td>6.287 mm per hour</td>
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Starting Time: 1547.00
Length of Sample: 60

Number of Drops
250.538  207.615  183.333  140.158  122.134  53.414  29.759  31.544  13.936  0.237
Z = 1.1981E-06 cm

Starting Time: 1548.00
Length of Sample: 60

Number of Drops
213.565  176.443  154.682  86.433  78.993  40.440  8.324
Z = 1.01503E-01 cm

Starting Time: 1549.00
Length of Sample: 60

Number of Drops
172.290  162.686  138.368  110.041  47.303  20.958  14.528  6.154
Z = 1.06271E-01 cm

Starting Time: 1550.00
Length of Sample: 60

Number of Drops
197.195  154.228  171.509  106.483  44.331  34.119  18.737  8.331  2.091
Z = 1.09504E-01 cm

Starting Time: 1551.00
Length of Sample: 60

Number of Drops
197.195  161.649  187.428  126.450  44.322  28.071  11.632
Z = 1.09590E-01 cm

Starting Time: 1552.00
Length of Sample: 60

Number of Drops
135.765  120.404  194.008  105.335  41.577  14.722  7.302  3.039
Z = 1.10383E-01 cm

Starting Time: 1553.00
Length of Sample: 60

Number of Drops
197.195  161.649  187.428  126.450  44.322  28.071  11.632
Z = 1.10383E-01 cm
### Raindrop Size Distribution Data for 7-31-1961

**NOTE:** Number of drops given in number per cubic meter per mm starting at 0.6 mm and in 0.2 mm classes.

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<th>Starting Time</th>
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**STARTING TIME 1106.00 LENGTH OF SAMPLE 60**

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**STARTING TIME 1107.00 LENGTH OF SAMPLE 60**

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**STARTING TIME 1108.00 LENGTH OF SAMPLE 60**

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**STARTING TIME 1109.00 LENGTH OF SAMPLE 60**

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**STARTING TIME 1111.00 LENGTH OF SAMPLE 60**

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<td>( I = 6.72 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 1.183 \times 10^{-6} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.324 \text{MM} )</td>
<td></td>
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</tr>
<tr>
<td>PRECIP INTENSITY =</td>
<td>2.111 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
<td>.1402 ( \text{E-01} ) ( \text{UB PER KM} )</td>
<td>( C = 1.042 )</td>
<td></td>
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</tbody>
</table>

**STARTING TIME**: 1120.00, **LENGTH OF SAMPLE**: 60

<table>
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<tr>
<th>NUMBER OF DROPS</th>
<th>12,800</th>
<th>143,210</th>
<th>298,418</th>
<th>243,079</th>
<th>85,278</th>
<th>29,763</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I = 6.81 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 1.174 \times 10^{-6} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.154 \text{MM} )</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>1.944 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
<td>.122 ( \text{E-01} ) ( \text{UB PER KM} )</td>
<td>( C = 1.263 )</td>
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**STARTING TIME**: 1121.00, **LENGTH OF SAMPLE**: 60

<table>
<thead>
<tr>
<th>NUMBER OF DROPS</th>
<th>30,935</th>
<th>216,547</th>
<th>184,645</th>
<th>35,202</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I = 6.95 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 1.38 \times 10^{-6} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.435 \text{MM} )</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>1.530 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
<td>.31 ( \text{E-02} ) ( \text{UB PER KM} )</td>
<td>( C = 1.174 )</td>
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**STARTING TIME**: 1122.00, **LENGTH OF SAMPLE**: 60

<table>
<thead>
<tr>
<th>NUMBER OF DROPS</th>
<th>64,004</th>
<th>196,413</th>
<th>97,600</th>
</tr>
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<tbody>
<tr>
<td>( I = 7.89 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 2.14 \times 10^{-6} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.767 \text{MM} )</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>2.74 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
<td>.16 ( \text{E-02} ) ( \text{UB PER KM} )</td>
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**STARTING TIME**: 1123.00, **LENGTH OF SAMPLE**: 60

<table>
<thead>
<tr>
<th>NUMBER OF DROPS</th>
<th>63,791</th>
<th>36,592</th>
<th>12,587</th>
<th>7,040</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I = 1.13 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 8.14 \times 10^{-7} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.764 \text{MM} )</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>1.10 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
<td>.21 ( \text{E-02} ) ( \text{UB PER KM} )</td>
<td>( C = 1.634 )</td>
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**STARTING TIME**: 1132.00, **LENGTH OF SAMPLE**: 60

<table>
<thead>
<tr>
<th>NUMBER OF DROPS</th>
<th>32,002</th>
<th>64,004</th>
<th>194,261</th>
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<tbody>
<tr>
<td>( I = 7.49 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 6.1 \times 10^{-6} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.769 \text{MM} )</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>0.76 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
<td>.65 ( \text{E-02} ) ( \text{UB PER KM} )</td>
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**STARTING TIME**: 1333.00, **LENGTH OF SAMPLE**: 60

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<th>NUMBER OF DROPS</th>
<th>32,002</th>
<th>64,004</th>
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<tr>
<td>( I = 6.7 \times 10^{-3} ) ( \text{MM CM}^{-3} )</td>
<td>( M = 5.1 \times 10^{-6} ) ( \text{Gm per cubic meter} )</td>
<td>( \text{UZERD} = 1.746 \text{MM} )</td>
</tr>
<tr>
<td>PRECIP INTENSITY =</td>
<td>0.67 ( \text{MM} ) ( \text{PER HOUR} )</td>
<td>ATTENUATION =</td>
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<tr>
<td>Starting Time</td>
<td>Length of Sample</td>
<td>Number of Drops</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>1149.00</td>
<td>60</td>
<td>57.177 82.779 63.517 14.081</td>
</tr>
<tr>
<td>1150.00</td>
<td>60</td>
<td>57.390 121.394 25.388 7.040</td>
</tr>
<tr>
<td>1151.00</td>
<td>60</td>
<td>25.388 89.179 0.000 7.040</td>
</tr>
<tr>
<td>1152.00</td>
<td>60</td>
<td>19.201 6.400 12.801</td>
</tr>
<tr>
<td>1153.00</td>
<td>60</td>
<td>31.789 57.390 25.388 7.040</td>
</tr>
<tr>
<td>1154.00</td>
<td>60</td>
<td>19.201 44.803 12.801</td>
</tr>
<tr>
<td>1155.00</td>
<td>60</td>
<td>19.201 44.803 12.801</td>
</tr>
</tbody>
</table>

Starting Time = 1149.00, Length of Sample = 60, Number of Drops = 57.177 82.779 63.517 14.081, PrecipIntensity = 0.25998E 02 Mm6M-3, Attenuation = 0.14937E-01 Gm Per Cubic Meter, Zero = 0.926MM

Starting Time = 1150.00, Length of Sample = 60, Number of Drops = 57.390 121.394 25.388 7.040, PrecipIntensity = 0.16182E 02 Mm6M-3, Attenuation = 0.11740E-01 Gm Per Cubic Meter, Zero = 0.710MM

Starting Time = 1151.00, Length of Sample = 60, Number of Drops = 25.388 89.179 0.000 7.040, PrecipIntensity = 0.91170E 01 Mm6M-3, Attenuation = 0.66298E-02 Gm Per Cubic Meter, Zero = 0.757MM

Starting Time = 1152.00, Length of Sample = 60, Number of Drops = 19.201 6.400 12.801, PrecipIntensity = 0.30749E 01 Mm6M-3, Attenuation = 0.21180E-02 Gm Per Cubic Meter, Zero = 0.921MM

Starting Time = 1153.00, Length of Sample = 60, Number of Drops = 31.789 57.390 25.388 7.040, PrecipIntensity = 0.12588E 02 Mm6M-3, Attenuation = 0.77288E-02 Gm Per Cubic Meter, Zero = 0.903MM

Starting Time = 1154.00, Length of Sample = 60, Number of Drops = 19.201 44.803 12.801, PrecipIntensity = 0.50838E 01 Mm6M-3, Attenuation = 0.41770E-02 Gm Per Cubic Meter, Zero = 0.768MM

Starting Time = 1155.00, Length of Sample = 60, Number of Drops = 19.201 44.803 12.801, PrecipIntensity = 0.50838E 01 Mm6M-3, Attenuation = 0.41770E-02 Gm Per Cubic Meter, Zero = 0.768MM
<table>
<thead>
<tr>
<th>NUMBER OF DROPS</th>
<th>6.547</th>
<th>6.547</th>
<th>28.162</th>
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<tbody>
<tr>
<td>Z = -1.004E+02 MM6M-3</td>
<td>M = .6786E+02 GM PER CUBIC METER</td>
<td>DZERO = 1.133MM</td>
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</tr>
<tr>
<td>PRECIP INTENSITY =</td>
<td>.106 MM PER HOUR</td>
<td>ATTENUATION = .62793E-03 DB PER KM</td>
<td>G = 1.004</td>
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**STARTING TIME**: 1156.00  
**LENGTH OF SAMPLE**: 60

<table>
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<th>NUMBER OF DROPS</th>
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</thead>
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<tr>
<td>Z = -3.9529E+00 MM6M-3</td>
<td>M = .48794E+03 GM PER CUBIC METER</td>
<td>DZERO = 0.729MM</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>.005 MM PER HOUR</td>
<td>ATTENUATION = .33634E-04 DB PER KM</td>
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<table>
<thead>
<tr>
<th>COEF</th>
<th>461.226093</th>
<th>SL</th>
<th>1.408212</th>
<th>STER</th>
<th>.432053</th>
<th>RPOS</th>
<th>1.037460</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNEG</td>
<td>-.469504</td>
<td>STERA</td>
<td>.416535</td>
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<td>COEFM</td>
<td>.053149</td>
<td>SLM</td>
<td>.901271</td>
<td>COEFD</td>
<td>1.555171</td>
<td>SLD</td>
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</tr>
<tr>
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<td>117.538</td>
<td>68.202</td>
<td>25.860</td>
<td>30.093</td>
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<tr>
<td>$I = 4.171E03$</td>
<td>$M = 6.833E06$</td>
<td>$DZER0 = 1.333$</td>
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</tr>
<tr>
<td>PRECIP INTENSITY</td>
<td>$= 1.278$</td>
<td>MM PER HOUR</td>
<td>ATTENUATION</td>
<td>$= 0.9217E-02$</td>
<td>DB PER KM</td>
<td>$G = 1.351$</td>
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</table>

<table>
<thead>
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<tr>
<td>NUMBER OF DROPS</td>
<td>56.592</td>
<td>110.316</td>
<td>96.235</td>
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<tr>
<td>$I = 3.305E03$</td>
<td>$M = 6.611E02$</td>
<td>$DZER0 = 1.310$</td>
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</tr>
<tr>
<td>PRECIP INTENSITY</td>
<td>$= 1.152$</td>
<td>MM PER HOUR</td>
<td>ATTENUATION</td>
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<table>
<thead>
<tr>
<th>STARTING TIME</th>
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</thead>
<tbody>
<tr>
<td>NUMBER OF DROPS</td>
<td>50.000</td>
<td>119.125</td>
<td>98.643</td>
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<tr>
<td>$I = 1.344E03$</td>
<td>$M = 3.918E02$</td>
<td>$DZER0 = 1.120$</td>
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</tr>
<tr>
<td>PRECIP INTENSITY</td>
<td>$= 0.624$</td>
<td>MM PER HOUR</td>
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<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>1320.00</th>
<th>LENGTH OF SAMPLE</th>
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<tbody>
<tr>
<td>NUMBER OF DROPS</td>
<td>115.006</td>
<td>120.124</td>
<td>102.203</td>
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<td>$I = 3.103E02$</td>
<td>$M = 3.064E02$</td>
<td>$DZER0 = 0.958$</td>
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</tr>
<tr>
<td>PRECIP INTENSITY</td>
<td>$= 0.440$</td>
<td>MM PER HOUR</td>
<td>ATTENUATION</td>
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</table>

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<tr>
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<tbody>
<tr>
<td>NUMBER OF DROPS</td>
<td>113.850</td>
<td>94.648</td>
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<tr>
<td>$I = 0.509E02$</td>
<td>$M = 2.362E02$</td>
<td>$DZER0 = 1.174$</td>
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</tr>
<tr>
<td>PRECIP INTENSITY</td>
<td>$= 0.346$</td>
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<tr>
<td>NUMBER OF DROPS</td>
<td>77.0607</td>
<td>114.730</td>
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<tr>
<td>$I = 2.917E03$</td>
<td>$M = 4.917E02$</td>
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<tr>
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<td>$= 0.862$</td>
<td>MM PER HOUR</td>
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<tr>
<th>STARTING TIME</th>
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<tbody>
<tr>
<td>NUMBER OF DROPS</td>
<td>127.460</td>
<td>150.510</td>
<td>106.988</td>
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<tr>
<td>$I = 3.374E02$</td>
<td>$M = 5.788E02$</td>
<td>$DZER0 = 1.174$</td>
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<tr>
<td>Starting Time</td>
<td>Length of Sample</td>
<td>Number of Drops</td>
<td>Precip Intensity</td>
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<td>NUMBER OF DROPS</td>
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<td>82.757</td>
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</tr>
<tr>
<td></td>
<td>$z$ = 33.066</td>
<td>03 MMN-M-3</td>
<td>$m$ = -2886E+01 GM PER CUBIC METER</td>
</tr>
<tr>
<td>PRECIP INTENSITY =</td>
<td>0.903 MM PER HOUR</td>
<td>ATTENUATION = -7250E+02 DB PER KM</td>
<td>$g$ = 1.553</td>
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**STARTING TIME 1415.00**

<table>
<thead>
<tr>
<th>NUMBER OF DROPS</th>
<th>55.901</th>
<th>107.104</th>
<th>101.984</th>
<th>63.612</th>
<th>65.369</th>
<th>52.045</th>
<th>49.947</th>
<th>13.258</th>
<th>4.335</th>
<th>9.308</th>
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<tbody>
<tr>
<td></td>
<td>$z$ = 1.6964E+04 MMN-M-3</td>
<td>$m$ = -13857E+00 GM PER CUBIC METER</td>
<td>$dzero$ = 1.595MM</td>
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</tr>
<tr>
<td>PRECIP INTENSITY =</td>
<td>2.870 MM PER HOUR</td>
<td>ATTENUATION = -31807E+01 DB PER KM</td>
<td>$g$ = 1.578</td>
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**STARTING TIME 1420.00**

<table>
<thead>
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</thead>
<tbody>
<tr>
<td></td>
<td>$z$ = 1.6654E+04 MMN-M-3</td>
<td>$m$ = -13773E+00 GM PER CUBIC METER</td>
<td>$dzero$ = 1.579MM</td>
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<tr>
<td>PRECIP INTENSITY =</td>
<td>2.803 MM PER HOUR</td>
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<td>$g$ = 1.492</td>
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**STARTING TIME 1425.00**

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<th>NUMBER OF DROPS</th>
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<th>56.424</th>
<th>44.497</th>
<th>34.657</th>
<th>5.653</th>
<th>7.479</th>
<th>3.058</th>
<th>1.577</th>
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<tbody>
<tr>
<td></td>
<td>$z$ = 1.5052E+03 MMN-M-3</td>
<td>$m$ = -70139E-01 GM PER CUBIC METER</td>
<td>$dzero$ = 1.363MM</td>
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<td>PRECIP INTENSITY =</td>
<td>1.297 MM PER HOUR</td>
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**STARTING TIME 1430.00**

<table>
<thead>
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<th>NUMBER OF DROPS</th>
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<th>51.706</th>
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<th>38.768</th>
<th>24.125</th>
<th>6.883</th>
<th>7.205</th>
<th>10.724</th>
<th>3.114</th>
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<tbody>
<tr>
<td></td>
<td>$z$ = 1.7732E+03 MMN-M-3</td>
<td>$m$ = -66270E-01 GM PER CUBIC METER</td>
<td>$dzero$ = 1.566MM</td>
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**STARTING TIME 1435.00**

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**STARTING TIME 1440.00**

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<td>Number of Drops</td>
<td>Precipitation Rate</td>
<td>Attenuation</td>
<td>G Value</td>
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**STARTING TIME 1620.00**
LENGTH OF SAMPLE 300

NUMBER OF DROPS
24,676 31,907 15,316 13,058 12,243 12,651 8,868 3,039

$Z = \cdot72194E \cdot03 MM6M-3$ M = \cdot442275E-01 GM PER CUBIC METER DZERO = 1.597MM

PRECIP INTENSITY = \cdot965 MM PER HOUR ATTENUATION = \cdot13817E-01 DB PER KM G = 2.095

**STARTING TIME 1625.00**
LENGTH OF SAMPLE 300

NUMBER OF DROPS
11,750 27,111 20,710 13,371 11,041 5,617 5,087 1,569

$Z = \cdot13532E \cdot03 MM6M-3$ M = \cdot18444E-01 GM PER CUBIC METER DZERO = 1.394MM

PRECIP INTENSITY = \cdot444 MM PER HOUR ATTENUATION = \cdot351568E-02 DB PER KM G = 1.084

**STARTING TIME 1630.00**
LENGTH OF SAMPLE 300

NUMBER OF DROPS
22,411 24,091 22,411 23,044 18,297 8,662 2,904 1,120 1,549

$Z = \cdot13193E \cdot03 MM6M-3$ M = \cdot20840E-01 GM PER CUBIC METER DZERO = 1.339MM

PRECIP INTENSITY = \cdot379 MM PER HOUR ATTENUATION = \cdot20520E-02 DB PER KM G = 1.374

**STARTING TIME 1635.00**
LENGTH OF SAMPLE 300

NUMBER OF DROPS
18,466 51,794 27,927 23,927 23,927 9,777 10,247 11,360 6496

$Z = \cdot31870E \cdot03 MM6M-3$ M = \cdot35658E-01 GM PER CUBIC METER DZERO = 1.516MM

PRECIP INTENSITY = \cdot898 MM PER HOUR ATTENUATION = \cdot62008E-02 DB PER KM G = 1.343

**STARTING TIME 1639.00**
LENGTH OF SAMPLE 300

NUMBER OF DROPS
46,395 39,950 23,159 17,784 37,426 15,709 4,197 9,677 1,549

$Z = \cdot30749E \cdot03 MM6M-3$ M = \cdot38380E-01 GM PER CUBIC METER DZERO = 1.395MM

PRECIP INTENSITY = \cdot746 MM PER HOUR ATTENUATION = \cdot62029E-02 DB PER KM G = 1.546

COEF = \cdot431.390629 SL = \cdot1.290082 STER = \cdot252870 RPOS = \cdot784247

RMEG = \cdot395615 STERA = \cdot315111

COEFK = \cdot02544 SLM = \cdot927797 COEFD = \cdot1.419884 SLU = \cdot415188

**** ALL INPUT DATA HAVE BEEN PROCESSED.
AT LOC 22167
ures was necessary in the specification of the computer output so that a wide range of values could be printed using the same format. The values are printed in either a decimal or an exponential form. The decimal data are obvious. A quantity such as .10264E 03 means .10264 x 10^3 or 103. Similarly .97282E-02 means .97282 x 10^{-2} or .00973.

The beginning time (MST) and the length of the sample (in seconds) are printed for each computation. Although the drop-size data were recorded continuously, it was necessary to summarize the drop-size spectra for finite time intervals. A 1-minute interval is used for most of the data, but for some a 5-minute interval was chosen. The number of drops is given as the number per cubic meter per mm in 0.2 mm class intervals starting at the class interval centered about 0.6 mm diameter. There are ten such classes in each row, viz. 0.6 to 2.4 mm for the first row and the second row begins at 2.6 mm. The reflectivity factor, $Z$, is given in mm^6 m^{-3}. The rain water content, $M$, for all drops greater than 0.5 mm diameter is given in g m^{-3}. The median volume drop diameter, DZERO, is given in mm. The precipitation intensity and attenuation are clearly labeled.

The attenuation, $A$, was determined from

$$A = 0.4343 \sum Q_t$$

where $Q_t$ is the total absorption cross-section. $Q_t$ was obtained for each drop diameter and for a wavelength of 3.2 cm and temperature of 18 C from a paper by Gunn and East.\(^1\) The units are in decibels km^{-1}. To make use of the attenuation information, it is necessary to know what portion of the rain system is represented by the particular sample.

The quantity, $G$, is given by

$$G = \frac{\sum ND^4}{(D_0^3 \sum ND^3)}$$

It is a quantity dependent on the width of the spectrum and was defined and used by Atlas and Bartnoff.\(^2\)

The rains of 27 July and 1 August 1961, were broken down into 1 min samples. Regression equations between $Z$, $M$, $D_0$ and $R$ were computed using the data from the rain on each day. The coefficients of these equations follow the last minute of data for each rain. The corresponding equations and coefficients are as follows

$$Z = (COEP) R^{SL}$$

$$M = (COEFM) R^{SLM}$$

$$D_0 = (COEFD) R^{SLD}$$

113
The units are identical to those defined earlier.

The standard error of estimate for the Z-R relationship was also computed. This was obtained by first computing R for each value of Z from the regression equation, and labeling this value $R_e$. If the actual precipitation intensity is denoted by $R_a$, then the standard error of estimate is given by

$$\text{STER} = (1/n \sum ((R_e - R_a)/R_a)^2)^{1/2}$$

where $n$ is the number of pairs of Z-R values. The maximum positive error ($R_e > R_c$) $\text{RPOS}$, and the maximum negative error, $\text{RNEG}$, are also evaluated for each rain. The quantity $\text{STERA}$ is given by

$$\text{STERA} = (1/n \sum ((R_e - R_a)/R_a)^2)^{1/2}$$

The July 31 rain was broken down into two parts. One minute distributions were used for the first 46 min and 5-min distributions were used for the last 250 min of the rain. The regression equations were computed separately for these two sections of the rain.

The two-theodolite method was used to measure the wind field below the cloud bases. A computer program was written to calculate the horizontal wind from these measurements. The physical location and orientation of the theodolites are shown in Fig. 5.1.

![Theodolite Diagram](Image)

Fig. 5.1. Two-theodolite baseline and location at Kent Ranch Station, Flagstaff, Arizona.

The computer output for the pibals taken on July 27, 31, and August 1, 1961
is given in Table 5.5. The following information will be helpful in the interpretation of the calculations.

The data, release time and approximate balloon lift are clearly stated for each release. The 4 numbers following the balloon lift are (1) the time interval between readings in seconds, (2), (3) the X and Y coordinates of the balloon release point (usually theodolite B which is also the origin of the coordinate system), (4) the number of readings for the ascent. The next 6-10 lines of information are the actual theodolite readings in the following order: horizontal angles for successive time intervals at A, elevation angles for station A, horizontal angles for station B, elevation angles for Station B. The time column is in increments of half minutes starting with the first half minute after the release. The mean height column gives the mean height of the balloon above the ground. The ZA and ZB columns give the height of the balloon as calculated from theodolite A and theodolite B elevation angles respectively. The X, Y coordinates give the projected location of the balloon on the horizontal plane (Fig. 5.1). The range difference is the horizontal distance in feet between successive locations of the balloon. The wind direction is given in degrees from north and complies with the standard meteorological convention for reporting wind direction. The wind direction and horizontal speed are average values for the layer between the balloon's current height and the height of the balloon at the preceding time interval. The last two columns give the angles α and β in the plane ABP (Fig. 5.2).

Fig. 5.2. Geometry of the two-theodolite system of triangulation.

Since the computation of the horizontal wind involves a term similar to \( \sin(\alpha - \beta) \) it is desirable to keep \(|\alpha - \beta|\) as large as possible. Reference to Fig. 5.2 shows that \(|\alpha - \beta|\) will always be greater than \(|\alpha' - \beta'|\) and therefore the plane ABP was used for determining the position of the balloon.

In some cases the results show a large variation between successive time
**Table 5.5**

**Computer Output for the Two-Methadone Pilot Balloon Bounding**

Walnut Ranch
Flagstaff, Arizona
July 27 to August 1, 1961

**Double Methadone Pilot Computations**

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<th>RANGE</th>
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## DOUBLE THEODOLITE PIAL COMPUTATIONS

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intervals. Some of these are probably real, especially during ascents in rain, but in others, observational errors are likely present. Unfortunately it is difficult to differentiate between these two cases. Since the time interval between readings is rather short it is suggested that the vectorial wind over a two minute interval should be taken in those cases in which large errors appear to be present. The position of the balloon in the horizontal plane may provide an indication as to whether an error occurred in the observation or not (see X-Y coordinate columns). Observational errors are magnified whenever the position of the balloon is in or near the vertical plane that contains the baseline A B.

Reduction of radar observations was limited by project funds to a cursory inspection of the photographic record. Comprehensive reduction of these data will go forward as new funds become available, starting with the data for 27 and 31 July and 1 August, and going further as funds allow and the potential of the data warrants.

Coordination with other cooperating groups is being maintained continuously. It is anticipated that the detailed analysis of the coordinated sets of observations of Project Hi-Cue 1961 in respect to raindrop-size spectra and the quantitative interpretation of weather radar echoes will form the basis for a doctoral dissertation.
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