NOAA Technical Memorandum NWS T&EL-13

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

Evaluation of Common Ceilometer Technology

Staff,
Observation Techniques Development
and Test Branch

Systems
Development
Office

Test and
Evaluation
Laboratory

STERLING, VA.

December 1971

Nation[illegible]ry Series

The Test and Evaluation Laboratory (T&EL) of the [illegible] Systems Development conducts experiments and tests to determine the suitability of newly developed equipment, instruments, and systems for field implementation by the National Weather Service (NWS). Results of tests and evaluations are provided to the other operating Offices of the NWS (Office of Meteorological Operations, Office of Hydrology, and National Meteorological Center) to guide field implementation activities, and to the Equipment Development Laboratory if further development is deemed necessary.

NOAA Technical Memoranda in the NWS T&EL series facilitate prompt distribution of scientific and technical material by staff members, cooperators, and contractors. Information presented in this series may be preliminary in nature and may be published formally elsewhere at a later date. Publications 1 to 9 are in the former series, ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM). Beginning with 10, publications are now part of the series, NOAA Technical Memoranda NWS.

NOTE--The National Weather Service does not approve, recommend or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to the National Weather Service, or to this publication furnished by the National Weather Service, in any advertising or sales promotion which would indicate or imply that the National Weather Service approves, recommends or endorses any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this National Weather Service publication.

Publications listed below are available from the National Technical Information Service, U.S. Department of Commerce, Sills Bldg., 5285 Port Royal Road, Springfield, Va. 22151. Price: $3.00 paper copy; $0.95 microfiche. Order by accession number shown in parentheses at end of each entry.

ESSA Technical Memoranda

WBTM T&EL 1 Final Report - Test and Evaluation of Berkeley Automatic Station. James E. Morris, January 1967. (Not Available)

WBTM T&EL 2 Final Report - Test and Evaluation of the Weather Bureau Radar-Telephone Transmission System (WM/RATTS-65). Robert E. Johnson, September 1967. (PB-176 532)

WBTM T&EL 3 Final Report - Test and Evaluation of the Mortarboard Psychrometer. Walter E. Hoehne and Roger A. Tucker, January 1968. (PB-177 689)

WBTM T&EL 4 Final Report - Test and Evaluation of a Facsimile Bandwidth Compression Technique. April 1968. (Not Available)

WBTM T&EL 5 Final Report - Test and Evaluation of the Video Integrator and Processor. R. C. Strickler, April 1968. (PB-180 765)

WBTM T&EL 6 Final Report - The AMOS V Observer Aid Test, Part I. Elbert W. Atkins and Walter E. Hoehne, October 1968. (PB-180 547)

WBTM T&EL 7 Final Report - Test and Evaluation of the Fischer and Porter Precipitation Gage. Walter E. Hoehne, August 1968. (PB-180 290)

WBTM T&EL 8 Final Report - The AMOS V Observer Aid Test, Part II. Elbert W. Atkins and Walter E. Hoehne, March 1969. (PB-183 810)

WBTM T&EL 9 Analysis of Visibility Observation Methods. Frederick C. Hochreiter, October 1969. (PB-188 327)

NOAA Technical Memoranda

NWS T&EL 10 Analysis of Cloud Sensors: A Manual Height Measurement System. Staff, Observation Techniques Development and Test Branch, March 1971. (COM-71-00549)

(Continued inside back cover)

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

NOAA Technical Memorandum NWS T&EL-13

EVALUATION OF COMMON CEILOMETER TECHNOLOGY

//
National Weather Service. Test and Evaluation Laboratory.

Staff, Observation Techniques Development and Test Branch

Systems Development Office
Test and Evaluation Laboratory

Sterling, Va.
December, 1971

UDC 551.508.762.001.4

551.5	Meteorology
.508	Meteorological instruments
.762	Cloud altitude measuring instruments
.001.4	Evaluation and testing

PREFACE

The principal investigator for this study was David H. George. Other members of the Observation Techniques Development and Test Branch participating in the technical effort were Matthew Lefkowitz, Branch Chief, Frederick C. Hochreiter, Marvin O. Hill, and Stephen E. Anderly.

Members of the Engineering Experimentation and Test Branch, particularly Robert J. McCann, Frank O'Donnell and Donald Lepsch, prepared much of the instrument description material, assisted in the evaluation of automation potential, and maintained the equipment to rigid specifications. Walter Hoehne, Branch Chief, Roger Tucker, Richard Bollinger, and Gene Hollingsworth, members of the Functional Experimentation and Test Branch, gathered and reduced the ASEA laser data summarized in this report.

The NOAA Computer Division's Analysis and Programming Branch provided us with data processing and computer services which allowed us to thoroughly investigate cloud height information. Special assistance was given us by Miss Sharon Love who wrote the programs necessary to process our cloud data.

Note: The National Weather Service of the National Oceanic and Atmospheric Administration does not approve, recommend, or endorse any product, and the evaluation and test results shall not be used in advertising, sales promotion, or to indicate in any way, either implicitly or explicitly, endorsement of the product by the National Weather Service.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EVALUATION OF COMMON CEILOMETER TECHNOLOGY

Staff, Observation Techniques Development and Test Branch

ABSTRACT

The National Weather Service Test and Evaluation Laboratory conducted a study which yields definitive, quantitative information about the performance of current off-the-shelf cloud height sensor technology. The reference for comparison in this study was the standard National Weather Service rotating-beam ceilometer, an instrument which uses the method of triangulation to determine cloud height.

Four cloud height sensors, employing two different principles, were studied. The first, a rotating-beam ceilometer, measures cloud height by triangulation through the use of a rotating beam of modulated light and a fixed detector. The second instrument was the Ceilograph, a German-built ceilometer which also measures cloud height by triangulation but uses a fixed beam of pulsed light and a scanning detector. The third instrument, the TNE 1502, is a French-built optical radar which measures cloud height by ranging techniques. The fourth ceilometer, a Swedish-built ASEA ruby laser, also measures cloud height by optical ranging techniques.

A modified rotating-beam ceilometer was also studied. The modification consisted of an experimental solid state amplifier in the RBC electronics.

Data collection lasted over a year at the Sterling Research and Development Center with cloud height samples taken as weather occurred and as personnel were available. Not all of the ceilometers were in operation at the same time, though. The ceilometers were sited so that no ceilometer would interfere with another. The instruments were set up to make simultaneous observations over 10-minute periods. Cloud height comparisons were made using mean cloud altitudes for each period, except for the laser, in which individual measurements were compared.

In addition to cloud height performance, the ceilometers were studied to determine ease of installation, maintenance requirements, susceptibility to noise and potential for use in an automated observing scheme. The study also investigated the effects of observation rate upon mean ten minute cloud height.

1.0 BACKGROUND

In the past, cloud height information has been considered primarily an element of aviation weather. Recent developments have broadened the need for cloud height and cover information. Today, such diverse applications as air pollution control, ecology studies, and weather modification rely to some extent upon cloud height as an important operational factor.

Most observations of cloud height made by the National Weather Service are human subjective estimates. Human estimates have several major disadvantages, some significant enough to demand substitute methods. Disadvantages include (1) increasing cost;

(2) lack of standardization caused by subjectivity and the presence of variations between observers, and; (3) an absence of observers at remote sites.

Recognizing the need to increase the objectivity and availability of weather observations, the Systems Development Office has embarked on an observation automation program. The long-range goal is the complete automation of surface weather observations. A short-term goal within that effort is increased information concerning performance of current sensor technology.

Responsibility for the development of objective observation techniques has been assigned to the Observation Techniques Development and Test Branch, part of the Test and Evaluation Laboratory. The work is being conducted in laboratory facilities at the Sterling Research and Development Center, Sterling, Virginia. Here, a variety of weather sensors are under study in order to determine their potential for automated and unattended operation. This report summarizes results of a study designed to develop definitive, quantitative information about the performance and characteristics of current cloud height sensor technology.

Four cloud height sensors, each employing different techniques, were studied. The first, a rotating-beam ceilometer, measures cloud height by triangulation through the use of a rotating beam of light and a fixed detector. The second instrument was the Ceilograph, a German-built ceilometer, which also measures cloud height by triangulation but uses a fixed beam of light and a scanning detector. The third instrument, the TNE 1502, is a French-built optical radar which measures cloud height by ranging techniques. The fourth ceilometer, a Swedish-built ASEA ruby laser, also measures cloud height by ranging techniques.

A modified rotating-beam ceilometer was also studied. The modification consisted of an experimental solid state amplifier in the RBC electronics.

The results reported here are not at all intended to mean that any of the ceilometers, the RBC included, gives unacceptable cloud height information, nor that any one ceilometer is "correct." For there is no "correct" cloud height as meteorologists have not yet accepted a fixed definition of cloud base nor is there an acceptable, absolute standard by which to determine cloud heights. Rather, our point is that each ceilometer uses techniques which yield a different measure of the same cloud field.

To this end, we have chosen the RBC as our reference for comparison--not because it is "correct"--but because within our goal of investigating current sensor technology, we must develop a basis for comparison. The RBC, because it is in such wide use in the United States, is the logical ceilometer to choose for developing this basis.

2.0 ROTATING-BEAM CEILOMETER

The Rotating-Beam Ceilometer is the first-line National Weather Service cloud sensor. The RBC, designed in the late 1940's, has been manufactured to NWS specifications by several firms. Widespread use has built up a good working knowledge of the RBC's characteristics and performance. Thus, it is well suited as a reference for comparison with other cloud height sensors in this study.

2.1 Description

A complete RBC system has three major components: A rotating projector; a fixed detector; and a recording or reporting device. The RBC (figure 1) measures cloud height by using principles of triangulation. The projector and detector must therefore be separated by a known distance, or baseline. Usually the baseline is in the range of 400 to 1,600 feet.

The projector consists of two identical 3×10^6 candela iodine vapor incandescent lamps. Each lamp is fixed at the 10-inch focus of a 24-inch diameter reflecting mirror. The 5 degree beam spread produces a 220-feet diameter beam at 2,500 feet altitude. The two mirrors are mounted back-to-back on a rotating shaft. A motor turns the shaft at 5 rpm so that emitted light sweeps upward from 0° to 90° ten times each minute.

Lamp light, modulated to 120 Hz. by a rotating shutter, is reflected downward from cloud particles into a fixed vertically pointing detector. The detector has no moving parts in order to minimize vibration induced noise. Another 10-inch focal length 24-inch diameter (5° field of view) mirror focuses the reflected light onto a lead sulfide photocell. The cell is enclosed in a housing fitted with an infrared transmitting cover glass designed to shield the cell from visible light. Visible light is further limited in some RBC's by the use of infrared pass cover glass on both projector and detector housings. Some RBC's also use a 5-inch-thick honeycomb filter, mounted just a above the detector photocell, to limit the amount of stray light which can enter the detector optics. Our RBC's were equipped with both of these options. Photocell current is amplified and formed into an a-c wave train in which amplitude is a function of signal intensity. The wave train may be input to an oscilloscope CRT or to a recorder which marks on electrically sensitive paper.

Physically the RBC is quite a bulky instrument. A large housing is needed to protect the rotating lamps, mirrors, and collecting optics. Both projector and detector housings stand about 5-feet tall and are over 3-1/2-feet square. Each unit weighs about 800 pounds.

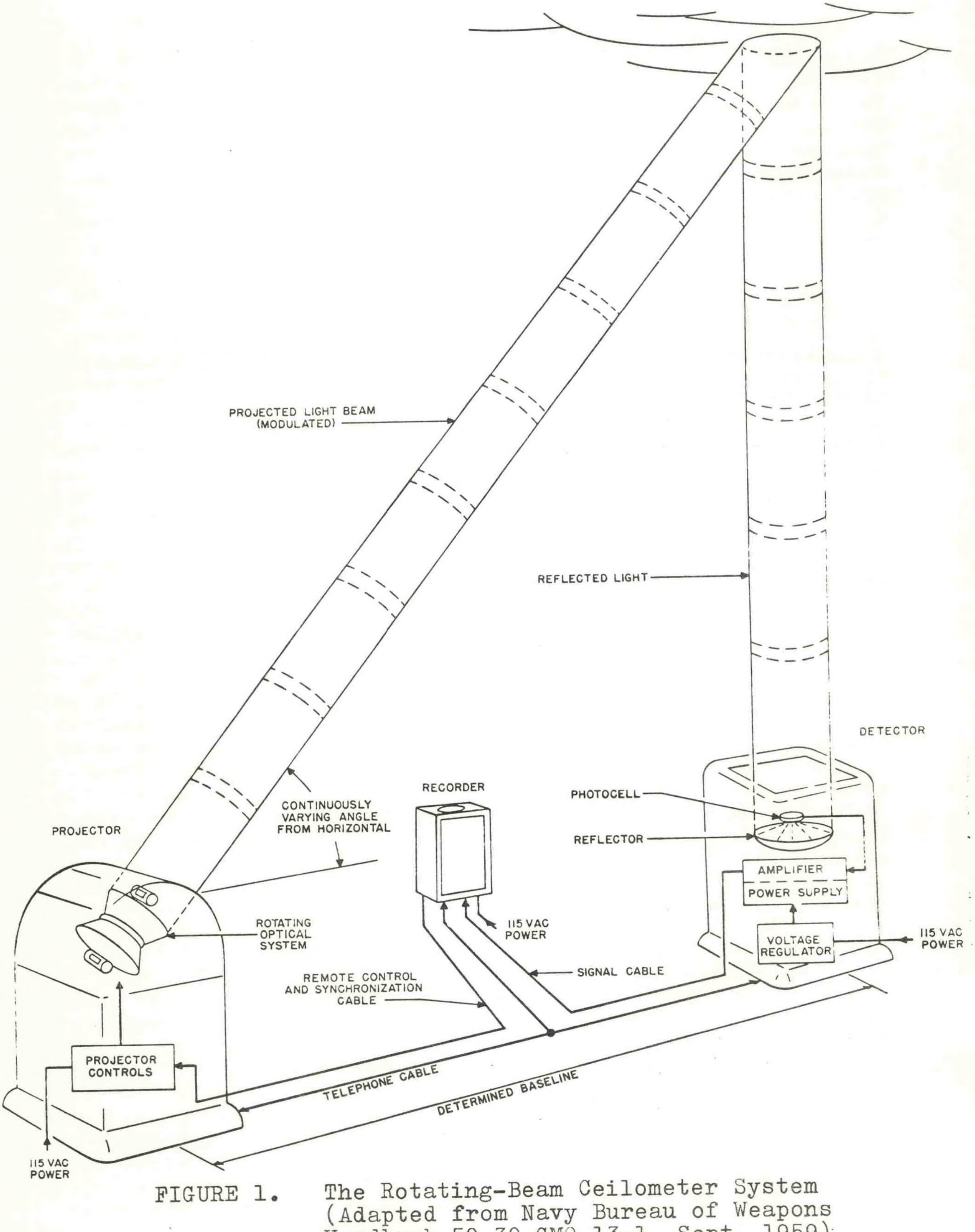


FIGURE 1. The Rotating-Beam Ceilometer System (Adapted from Navy Bureau of Weapons Handbook 50-30 GMQ 13-1. Sept. 1959)

The detector top is sloped away from the projector to reduce stray light and to promote water runoff. A 1000-watt thermostatically controlled heater and blower prevent ice and snow accumulation atop the detector cover glass. A tube-type signal amplifier, power supply, and voltage regulator are contained in the bottom of the detector housing. Four doors in the housing make components easily accessible.

The RBC projector has a curved top which prevents precipitation build-up. Heaters are not needed in the projector as the rotation motor and lamps generate sufficient heat to melt snow and ice. A ventilator cut in the housing, plus an electric fan, permit warm inside air to escape. Two doors in the projector housing make for easy access. In addition, the entire top half of the housing tilts back to expose the optics and drive mechanisms.

The RBC measuring range begins between about 10° and 20° angular elevation and goes to approximately 84°. The actual lower limit is the result of cover glass cutoff and measurements are frequently made at elevations lower than 20°, while the upper limit is but a rule-of-thumb derived from assumptions of a 1° instrument error and a maximum allowable cloud height measurement error of 20% [1].

Though based strictly on assumed measurement accuracy, about 84° elevation, or ten times the baseline, is generally accepted as the upper limit for triangulation type ceilometer measurements. In practice however, actual maximum cloud height is a function of many other factors. For example, light intensity, cloud density, opacity of the intervening atmosphere, as well as detector field-of-view and sensitivity play important roles in restricting the upper limit of ceilometer measurements. In the U. S., ceilometer-determined cloud heights up to ten times the baseline may be reported as "measured," while greater heights are used to aid the human observer in estimating cloud altitude.

2.2 Installation

Both the RBC projector and detector require large, solid mounting pads. Minimum requirements are for two poured concrete squares, six feet long on each side by two feet thick. Each housing is anchored by four 1/2-inch diameter bolts.

Both projector and detector need 110 volt a-c power lines. The RBC requires two pairs of cables to projector and detector: one pair for signal, the other for control. Signals from the detector may be sent via land lines to an indicator or recorder several miles away. The actual distance, of course, is determined by the quality and amplification of the land line network.

2.3 Maintenance

Frequent regular maintenance is needed if an RBC is to be kept in top operating condition. The following maintenance is taken from the Instruction Manual for RBC, 1967.

Weekly:

Clean glass covers and mirrors.

Check lamps, modulator shutter and rotation drive motor.

Monthly:

Check projector optics alignment, and rotation mechanism.

Each three months:

Check entire projector drive system.

Half-yearly:

Inspect projector shaft and bearings.

Inspect projector and detector cables and connections.

3.0 CEILOGRAPH

The Ceilograph (figure 2) is a triangulation-type ceilometer that uses a fixed vertically pointing light beam and a scanning detector. The manufacturer, Impulsphysik GmbH, of Hamburg, Germany, loaned us a Ceilograph for these studies. The Ceilograph employs pulsed-light techniques with modern, solid state circuitry to output cloud height.

3.1 Description

The Ceilograph uses a light projector and a light detector separated by a known baseline. The usual Ceilograph baseline, 250 feet, is designed to allow cloud measurements from 100 to 2,500 feet altitude (22° to 84° elevation).

The vertically pointing light source is an FT-230 Xenon flash lamp which produces light in the visible but with peak intensity at about .9 microns. The lamp flashes through a discharge capacitor 4 to 6 times per second with intensity of 10^7 to 10^8 candelas/cm^2. Flash rate is adjustable by varying a 220 VDC transformer which in turn loads a discharge capacitor. The flash lamp is fixed at the 10-inch focal point of a 21-inch diameter reflector. Access to the lamp is through a service door in the projector housing.

The projector housing itself is fairly large. Made of cast aluminum, the circular housing is about 4-feet high by 2-1/2-feet in diameter. At the base are three adjustable legs which are used for leveling. The top cover glass is sloped to permit water runoff. Under the glass, which can be removed, are three thermostatically controlled 500-watt heaters. The heaters, set to turn on at 25°C., provide enough energy to melt frozen and freezing precipitation on the cover glass. Also accessible under the cover glass is a 4-inch thick honeycomb filter which collimates the light beam to 12 minutes of arc. This makes the light beam about 5-feet wide at 2,500 feet altitude.

A projector control panel door is located near the bottom of the projector housing, directly below the mirror access door. The control panel has power on/off and remote/local control switches and indicator lights, circuit breakers, fuses, total accumulated running-time meter, and a pulse rate adjustment control. An interlock switch on the control door shuts off lamp power whenever the door is open. In addition, a bracket holds the upper compartment door closed until the control panel door is open and lamp power off.

The Ceilograph detector scans up and down the projector light beam from 22° to 89° once each minute. The detector receives

Receiver

Projector

Figure 2. The Ceilograph Receiver and Projector

light pulses reflected from clouds during both upward and downward scans. The scanning mechanism is a motor-driven shaft which carries an off-center cam. Rotating the cam produces a variable scan rate which is linear in logarithms, the faster rate being in the lower elevations.

A removable honeycomb filter, just inside the detector cover glass, reduces the amount of scattered light directed to the detector cell. Next to the honeycomb are two 5-inch diameter quartz lenses which focus reflected light pulses through a .6 mm (1° view) aperture onto an EG&G SGD-44 photodiode. A 250-watt heater, mounted between the lenses, provides temperature control to discourage lens condensation. Electrical pulses, converted from light pulses by the photodiode, are fed to a four-stage 80 db. gain broadband amplifier which is designed to recognize only pulses produced by the Xenon projector. Amplifier output is fed to a white noise amplifier which amplifies photodiode noise and uses the resultant voltage as an automatic amplifier gain control (figure 3). As photodiode noise increases, such as during daytime conditions, amplifier gain decreases.

A receiver threshold adjust is provided at this point for selecting a favorable signal to noise ratio. The pulse amplifier output triggers a monostable multivibrator which produces constant length pulses. The pulses drive a relay which produces recording pulses in the Ceilograph recorder.

Receiver electronics and detector optics are contained in a 5-inch diameter by 1-1/2-foot long aluminum tube. Access to the electronics is through a rear cover while the optics may be reached after removing the detector cover glass. The scanning tube is bolted to a rotating shaft which extends from the main support column. The column, which contains sights and levels for aligning the detector, is about five feet tall.

The Ceilograph strip chart recorder uses dry electrolytic paper. The recorder pen, which travels synchronously with the scanning detector, burns one spot on the chart for each light pulse detected.

The recorder contains controls for turning the Ceilograph on and off, a "power on" lamp, an accumulated running-time meter and a small lamp which flashes when cloud return pulses are recorded. In addition, the recorder has a synchronization check. A small button, when depressed, causes the detector amplifier to output a reference pulse when detector elevation equals 50.2° or 300 feet altitude. The mark indicates whether or not both recorder pen and detector are synchronized.

Another feature of the recorder is a safety interlock switch which removes power to the recorder pen whenever the recorder door is open.

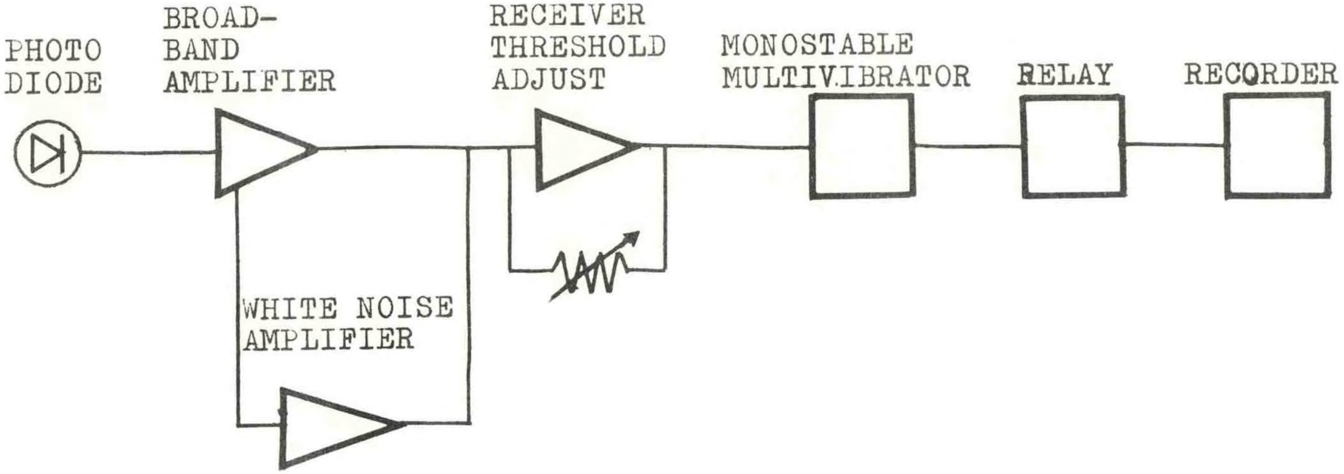


FIGURE 3. Ceilograph Receiver Block Diagram

3.2 Installation

Both projector and detector are installed outdoors, each on its own solid, permanent footing. Three bolts anchor each unit to its pad. The recorder must be installed indoors but may be located up to six miles away.

Three sets of cables are needed with the Ceilograph. One set provides for signal and control between projector and detector. A second set supplies the detector with power from the projector. The third set of cables runs between the projector and recorder to carry signals and control instructions.

3.3 Maintenance

The Ceilograph requires less frequent maintenance than the RBC. The most frequent maintenance, as with most ceilometry and visibility instruments, concerns lens and mirror contamination. In "clean" localities, infrequent maintenance is required. The following Ceilograph scheduled maintenance is recommended by the manufacturer however:

Biweekly or as needed:

- Clean glass covers, mirrors and lenses.

Half-yearly

- Replace detector desiccant.
- Grease detector drive worm gear.

Yearly:

- Grease detector drive bearings.

4.0 OPTICAL RADAR TNE 1502

The French National Meteorological Service loaned us an optical radar cloud height measuring system, TNE 1502. Techniques employed in this ceilometer's light source, in processing cloud returns and in converting returns to heights are considerably different from those of other instruments with which we are familiar.

4.1 Description

The TNE 1502 optical radar (figure 4) is manufactured by Compagnie Des Computeurs. Cloud height is determined from the transit time required for a light pulse to travel from the ground-based projector to a cloud, be reflected, and then travel downward to the ground-based receiver. Because triangulation is not involved, projector and receiver housings are placed but 25 feet apart. Large projection and collection optics require fairly bulky housings, about 3-feet square by 2-1/2-feet high.

A TNE 1502 system consists of a projector, projector power supply, receiver, conversion unit, and recorder.

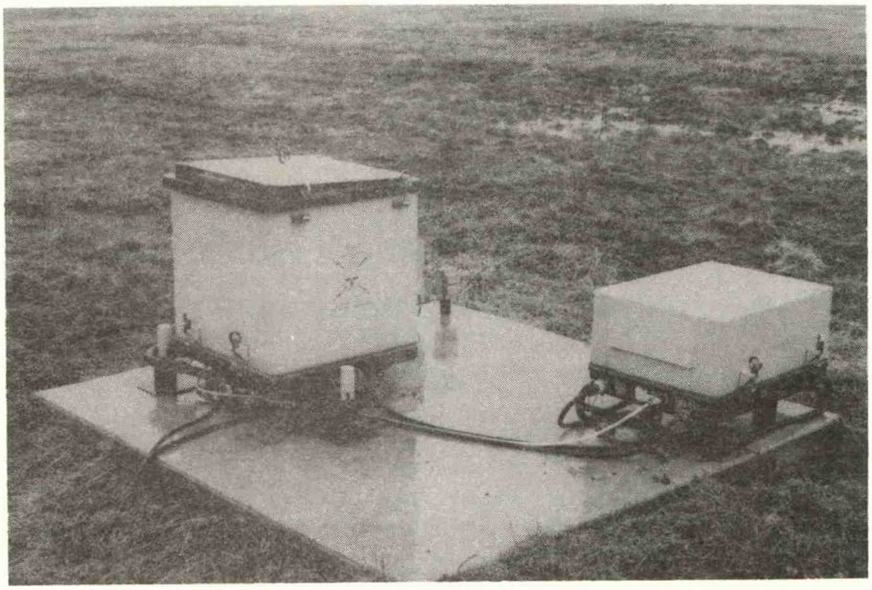
We go into some detail in describing these components as optical radar ranging methods are significantly more complex than those found in triangulation ceilometers.

The TNE 1502 generates blue to ultraviolet light from a series of spark flashes between two tungsten electrodes. The electrodes are fixed at the focus of a 20-inch parabolic mirror. Peak power dissipated in each spark is about 1 Mw over a 2 microsecond interval. Pulse length is about 1,968 feet. The spark rate, 30 Hz., occurs at 1/2 the power supply frequency so that 360 light pulses are generated during each 12-second observation.

The parabolic mirror, focal length 10 inches and diameter 20 inches, forms a light cone of 55 minutes (.92°) divergence. This gives a beam diameter of approximately 50 feet at 3,000 feet altitude. The beam is collimated by adjusting the height of the spark gap assembly above the mirror.

The projector housing is a rectangular metal box mounted on three leveling jacks with a tilted glass top designed to shed rainwater. Internal components are kept dry by an air heater and a ventilation system. Two bubble levels are mounted on the mirror frame for leveling. Pulsed light reflected downward from atmospheric particles is collected by the receiver parabolic mirror. Identical to the projector mirror, the receiver mirror focuses the light onto a cesium-antimony photoelectric cell. The photocell, which follows the S-4 curve, has maximum

Projector Power Supply



Receiver Conversion Unit

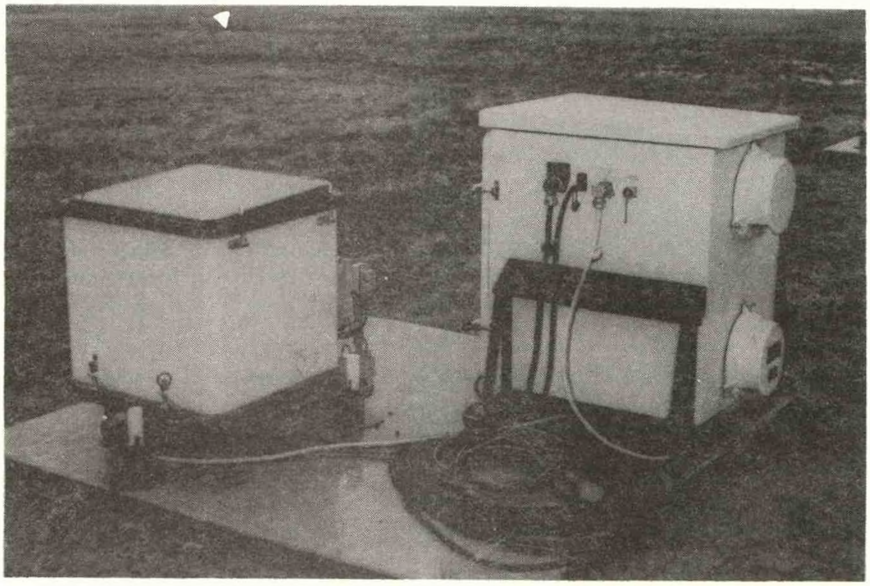


FIGURE 4. TNE 1502 Field Componets

sensitivity in the blue range. Between soundings the cell is protected from stray radiation by a solenoid-actuated mechanical shutter. Though otherwise identical to the projector mirror, the receiver mirror has a 1° 55' field of view. The larger field is desirable in order to collect as much of the reflected pulsed light as possible. The larger field is achieved by using a fairly large field stop over the photocell and by mounting the cell slightly distant from the mirror focal point.

The receiver housing is similar to that of the projector in general design and includes a leveling system, air heater and ventilation system.

The conversion unit contains several components. The controller, or automation chassis, controls system operation. By using motors, cams, and relays the automation chassis programs each observation. It simultaneously controls the projector spark and receiver shutter, starts the recorder, synchronizes the recorder with the scan pulse, selects the correct gate for whichever of the two (1500 m or 500 m) measuring ranges is being used, and performs calibration checks.

An 18-cell (.065 msec. each) delay line between the receiver and the conversion unit video amplifier compensates for delays in triggering coincidence and calibration circuits and adjusts for delays caused by varying connection cable lengths. The 1.2 Mc. bandwidth video amplifier, as other electronics in this system, uses only vacuum tubes. Gain of the four-stage video amplifier is automatically regulated by a noise amplifier to maintain a constant noise amplitude. A diode in the noise amplifier circuit limits video amplifier gain. This is designed to insure stable nighttime operation.

Cloud echo detection occurs when the video amplifier output is coincident with a scan pulse generated by the TNE 1502 conversion unit. The scan pulse, actually a traveling gate, allows those cloud echo pulses which are coincident within the 66-foot (.15 microsecond) gate interval to pass into the recorder unit. The gate itself travels 16 feet with each succeeding projector light pulse. At pulse 1 then, the TNE 1502 can detect cloud echoes through the interval from 100 feet to 166 feet. At pulse 2, 1/30 second later, the interval has traveled 16 feet and covers the range 116 to 182 feet. The gate travels in like manner for 10 seconds until the maximum height of 4,921 (1500 m.) feet is reached. On the 1,640-foot (500 m.) range, the gate travels about 5 feet with each pulse.

A unique automation feature of the TNE 1502 is the calibration generator. Once every eight soundings, or whenever the measuring range is changed, the conversion unit directs a set of calibration pulses to the coincidence circuit. The calibration pulses appear on the recorder at 328-foot (100 m.) intervals. The calibration generator thus checks the synchronization of the traveling gate and projector light pulses.

Another feature of the TNE 1502 is its cloud presence indicator. The indicator shows presence of clouds when they are detected at the end of each 10-second sounding. The cloud presence mark appears on the recorder independent of the measuring range selected.

Conversion unit components are mounted in a watertight rectangular metal box mounted on a tubular cradle. The air heater and ventilation system is similar to that of the projector and receiver, though a forced draft system is needed to cool the many vacuum tubes.

The TNE 1502 cloud height recorder uses metalized paper as a permanent record. The stylus, controlled by the automation chassis, travels across the paper conducting an electrical current whenever a cloud echo is detected.

4.2 Installation

The conversion unit, receiver, projector, and projector power supply are installed outdoors on permanent footings. The projector and receiver are about 25 feet apart. For the convenience of cable runs the conversion unit is located between the projector and receiver with the power supply placed near the projector. The recorder must be set indoors, but may be several miles distant. The TNE 1502 requires nine conductors for signal and control functions.

4.3 Maintenance

The TNE 1502 operating manual suggests the following scheduled maintenance:

Weekly or as needed:
  Adjust electrodes.
  Clean glass tops.
  Clean air filters in projector, power supply, receiver and conversion unit.

4.4 TNE 1502 Accuracy

We had the opportunity to check TNE 1502 measuring accuracy. By accuracy, we mean the observed error when the distance to a known target is measured. For this test, we laid both projector and receiver over on a side, aimed at a fixed target, and evaluated the returns. Our target was a large van, one side of which was covered with 12' x 7' reflective aluminum foil (figure 5).

We used an oscilloscope for signal display as the TNE 1502 recorder could not give us the required resolution. The oscilloscope read to an accuracy of ±49 feet, or ±.1 microsecond. We also measured the recorder signal return pulse as a check of system data translation precision.

The maximum distance at which we could detect returns from the target was 3,200 feet. We believe this was due to imprecise alignment of the TNE 1502 with the target vehicle and to the small target site relative to beam area at greater distances. Test results are shown in table 1.

The TNE 1502 receiver signal gave good results with error less than 100 feet even at the 3,200-foot range. Recorder precision, however, was poor. The 1600-foot measuring scale was particularly poor as the largest errors, 18%, occurred at the greatest distances. The 18% error at 100 feet distance would have gone unnoticed were the signal not displayed on an oscilloscope, however. The recorder by itself would have shown 100 feet. The 5,000-foot scale gave acceptable accuracy with the largest errors at smaller distances. The 4.6% error extrapolated to 5,000 feet would cause only a 250-foot difference. This is still only one-half of the observation resolution required of human observers by FMH #1 [2] when 5,000-foot cloud bases are present.

TABLE 1

TNE 1502 Accuracy

Distance to Known Target in Feet	Indicated Receiver Distance in Feet	% Error	1600-Ft. Scale Recorder Distance in Feet	% Error	5000-Ft. Scale Recorder Distance in Feet	% Error
100	100	0	82	- 18	138	+ 38
200	196	- 2	197	- 1.5	197	- 1.5
400	495	- 1.25	394	- 1.5	492	+ 23
800	789	- 1.4	656	- 18	738	- 7.5
1600	1579	- 1.3	1312	- 18	1673	+ 4.6
3200	3249	+ 1.5			3346	+ 4.6

FIGURE 5. Optical Radar Reflective Target

5.0 LASER CEILOMETER

A ruby laser ceilometer, manufactured by ASEA of Vasteras, Sweden, was loaned to us for a two-month period during late spring 1971. The duration of study greatly limited our experiences with the ceilometer. Relative to our work with the other three instruments, our look at the ASEA laser was most cursory.

5.1 Description

The ASEA Ceilometer, type YLAMP (figure 6), determines cloud height in the same manner as the TNE 1502 and is in fact a type of optical radar. The transit time required for a light pulse to travel from the projector to a cloud and return to the detector is directly proportional to the cloud height. In the ASEA ceilometer, a Q-switched ruby laser produces a brief pulse (30 nsec.) of nearly monochromatic visible (6943Å) light. The beginning of a pulse starts a high-speed counter which operates until the photomultiplier detector receives reflected laser light. The ceilometer then makes a simple scale conversion from transit time to cloud height up to a maximum of 16,000 feet.

The small size of the solid state transceiver electronics and ruby laser are shown to good advantage in the compactness of the ceilometer. The entire unit is housed in a single circular cast aluminum container which measures less than three feet high by about 1-1/2 feet in diameter.

A 3-foot tall transmitter shield extends above the housing to protect the laser from direct sunlight and to prevent people from looking directly into the laser beam.

The ceilometer housing sits on three legs which are adjustable for leveling. Leveling is not critical, however, as a 10° tilt from vertical produces only a 2% error in measured cloud altitude. The housing also has an access door which allows for easy entry to the transceiver and laser components.

Safety can be a problem with any high intensity light source or electronics equipment. The narrow, high intensity (1.5 milliradian, 2 megawatt) laser beam, however, poses a particular problem in that occupants of overflying aircraft could suffer possible eye damage if they were to somehow look directly down into the beam during a 30 nsec. light pulse. The probabilities of such exactness are extremely remote however. Yet since the potential exists no matter how remote, adequate care must be taken when using the laser ceilometer to ensure that the overhead area is free of aircraft.

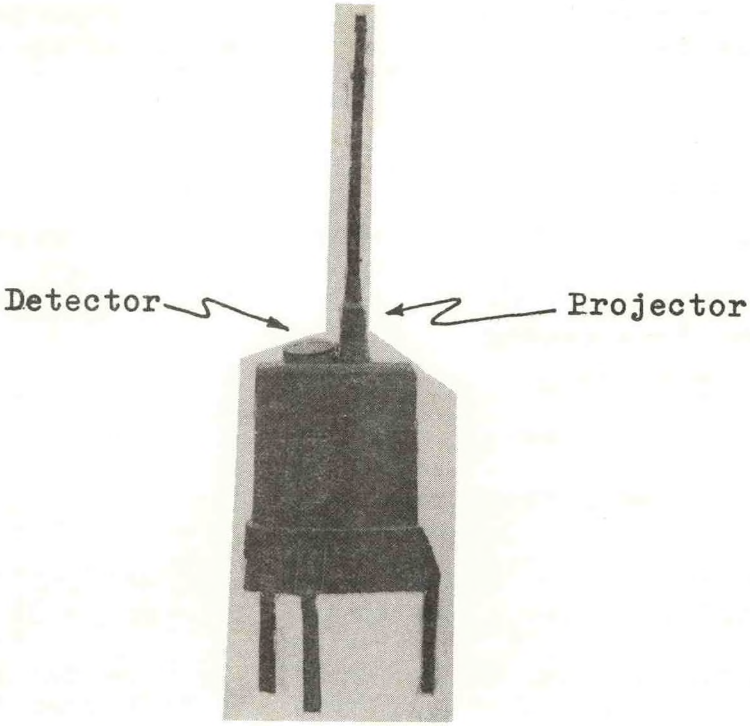


FIGURE 6. Laser Ceilometer

5.2 Installation

Installation is simple. One man can set up the ASEA laser since it is composed of but a single 110-pound unit. A large mounting pad is not needed. A 220-volt power supply cable services the ceilometer. A second cable carries cloud return information to a recorder or oscilloscope which may be placed up to 3 miles away.

5.3 Maintenance

Manufacturer recommended maintenance is as follows:

As needed:

- Clean glass covers.
- Replace desiccant.

Every 20,000 to 25,000 shots:

- Replace laser flash tube.

Neither our brief experience nor the manufacturer's literature indicates just how long a desiccant cartridge will last.

The two months in which we had the laser were devoted primarily to data acquisition and little time was left over for engineering analyses. We especially wanted to perform an accuracy test, as was done with the TNE 1502. This was eliminated, however, because the laser had to be returned. Other researchers, though, have found ASEA accuracy to be in the range of that found for the TNE 1502 [3].

6.0 MODIFIED RBC

We installed a solid state amplifier in a 400-foot RBC detector labeled D2. The amplifier, designed and built as an experimental model by the Equipment Development Laboratory, replaced the standard old style tube-type RBC amplifier. Advantages of the solid state amplifier include low maintenance and low amplifier noise because of the solid state components, and a fixed voltage gain of approximately 100 db. The amplifier has a 33 Hz. bandwidth, centered at 120 Hz.

7.0 DATA HANDLING

We acquired all data for this evaluation at the National Weather Service's Sterling Research and Development Center near Sterling, Virginia. The field site (figure 7) is located on approximately 475 acres of gently rolling land. Instruments were placed in the field site on the basis of convenience to electrical and signal lines. Distances between ceilometers were such that light projected from one instrument could not be sensed by another.

Our first data acquisition season began in June 1969 and ended in March 1970. Our second season ran from February 1971 to April 1971. We attempted to sample the occurring weather and cloud fields in a manner which would give us a representative mix of conditions. We were most successful in the mix of RBC data and least successful with the laser.

Field measurements were taken as weather and cloud cover occurred and as data acquisition personnel were available. The lack of suitable weather conditions as well as manpower restricted much of our data gathering to daytime, precipitation conditions. This was particularly true with the Ceilograph. We did gather a reasonable no-precipitation sample with the optical radar, however. The short time available with the laser ceilometer made but the most meager data sample possible.

All equipment was maintained to manufacturer's standards by experienced electronic technicians. Regular maintenance schedules were followed and all malfunctions noted.

7.1 Data Reduction

We used a four-trace oscilloscope CRT to display ceilometer (except the laser) output signals. The signals, one for each ceilometer, were photographed on continuous motion 35 mm. strip film. Ceilometer signal parameters were measured on the developed film and reduced to usable form for analysis.

To make data reduction easier and to provide acceptable resolution, three sets of reference marks were recorded on the film (figure 8). Small markers, produced by a flashing neon lamp inside the oscilloscope camera, divided each second into 120 equal parts. Each $1/_{120}$ second corresponds to 1/4 degree of RBC rotation. A larger second set of markers divided the film into 1/6 second intervals which correspond to 5 degrees of RBC rotation. Third, the beginning (0°) and end (90°) of each RBC mirror rotation was marked. The large 0° and 90° markers occurred in sequence 3 seconds apart.

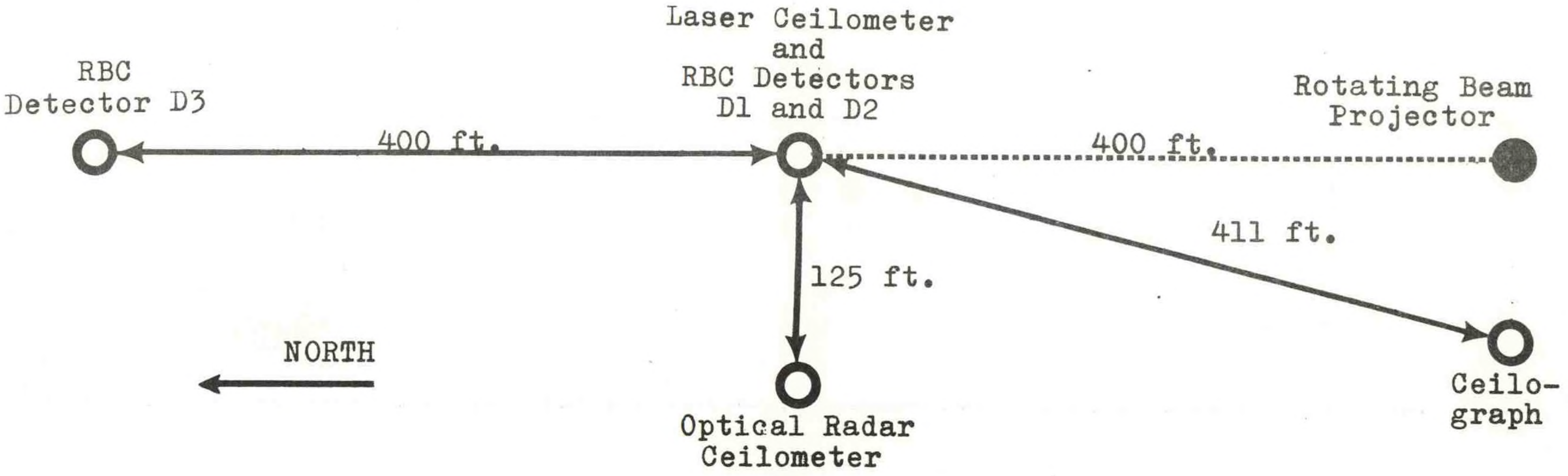


FIGURE 7. Ceilometer Experiment Site Layout - Sterling Research and Development Center

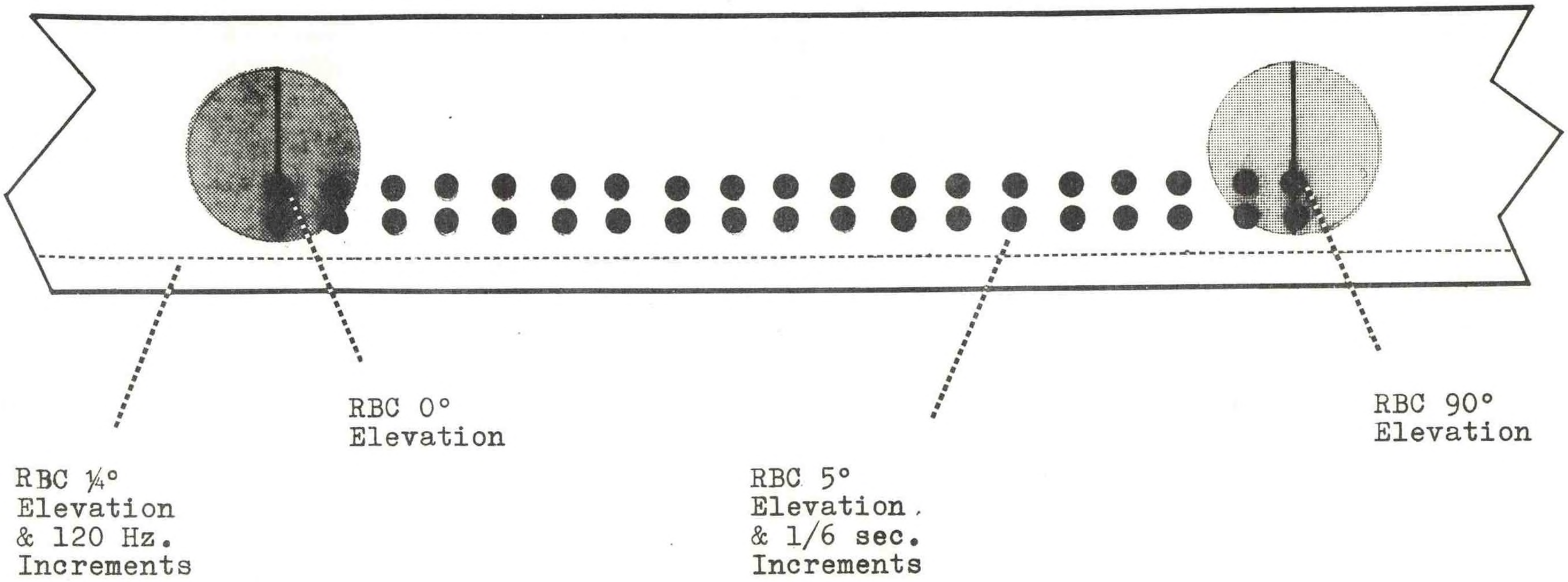


FIGURE 8. Time Scale Reference Marks on Oscilloscope Film

It was quite easy to determine at what time during a ceilometer observation a signal return occurred by using the relationship that time is directly proportional to film length. The altitude of a return could then be determined from the time of return once the time versus altitude relationship was found. For ceilometers which use triangulation, both time versus angle and angle versus altitude functions must be known.

For RBC's, the return altitude h is given by

$$h = b \tan 30t \quad (\text{ft.}) \tag{1}$$

where b is the ceilometer baseline and t the scan time (0 to 3 sec.) at which the cloud return occurred.

7.2 Return-Height Reduction

Typical RBC signal return envelopes, composed of 120 Hz. a-c waves, are shown in figure 9. We assumed that the maximum signal amplitude in an RBC return envelope corresponds to the cloud altitude. Some judgment was involved in determining if a signal was to be considered a return envelope. Generally if the maximum amplitude exceeded the noise level by a factor of 2, and if there were three or more increasing and then decreasing a-c waves on either side of the maximum amplitude, we considered a return envelope to exist.

Selection of multiple returns in a single RBC scan required greater judgment. A second (or third or fourth) return was selected only if distinct envelopes were recognizable. Usually, recognizable envelopes were separated by several cycles having amplitudes less than 1/2 that of the maximum envelope cycle. Figure 9 shows an example of double RBC return.

Once a return envelope was determined to exist, the point of maximum amplitude was marked and the angular elevation of the RBC in 5 degrees plus 1/4 degree increments noted on a data reduction sheet. Data from the sheet were punched onto data cards and used as input to the NOAA CDC 6600 computer which then computed and printed the elevation angle and height of each return as well as mean angles and heights for each data period.

Returns measured by the TNE 1502 appeared as d-c pulses (figure 10). The pulses varied in duration from 1/30 second up to several seconds. A complete observation takes 12 seconds. While the projector produced light pulses for 12 seconds, the receiver remained inactive during the first second, was open

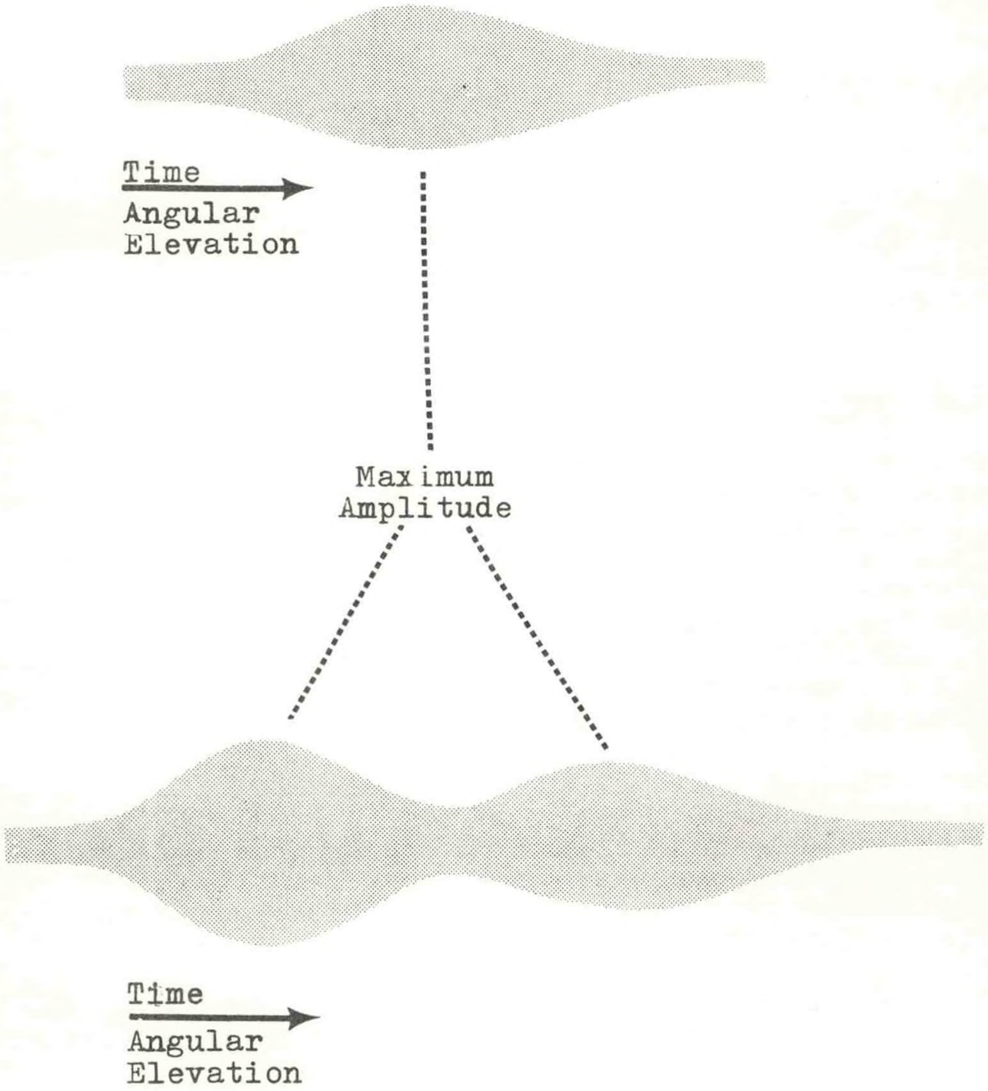


FIGURE 9. Typical RBC Return Envelopes

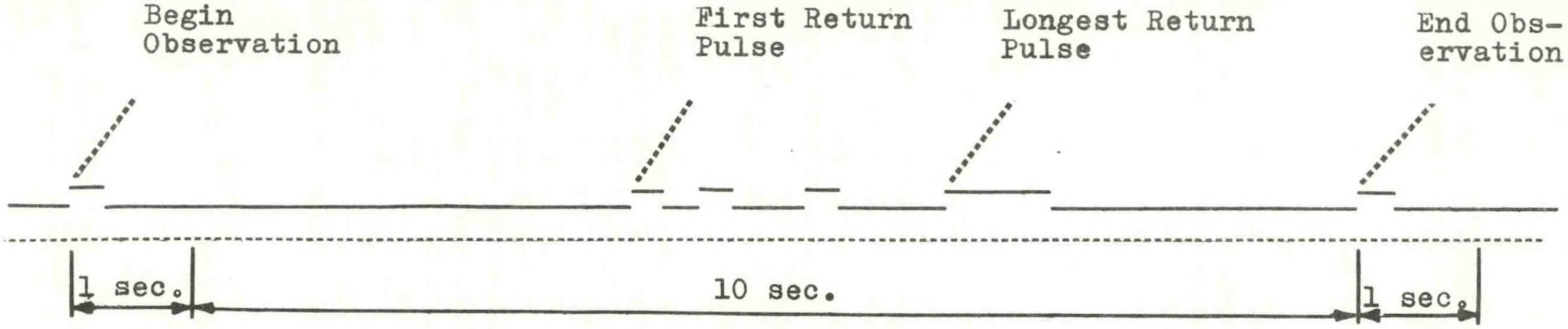


FIGURE 10. Typical TNE 1502 Cloud Height Observation

to accept returns during the next 10 seconds, and was inactive during the final second while the system reset for another observation.

In normal operation, the TNE 1502 observes at the rate of eight per 15 minutes. We found this to be much too infrequent for our application, as we could record only 3 observations per 6-minute roll of film. We also found that the data could be reduced and cloud heights determined more simply if the system could begin observing coincident with the reference RBC sensor. We therefore modified the TNE 1502 to observe once each 24 seconds, with each observation beginning at 0 degrees RBC elevation. This arrangement gave us 15 observations per 6-minute roll of film and brought the RBC and TNE 1502 to a common time base.

Figure 10 shows an example of a typical TNE 1502 output. The altitude indicated by a pulse is determined from the linear relationship between time of return and altitude. Four different points may be taken for the TNE 1502 cloud height measurement: the first return pulse and the beginning of the longest pulse, which we felt might be related to the cloud base, and; the end of the longest return pulse and the final pulse, which we thought might be related to cloud penetration. Later, during data analysis, we found that the beginning of the longest pulse yielded more consistent, reliable cloud heights. This was the height used in data anslysis.

Cloud returns observed by the Ceilograph also appeared as d-c pulses (figure 11). The length of each pulse is constant as is amplitude. According to the manufacturer, the first pulse indicates cloud base while the final pulse in a series signifies the limit of vertical visibility into the cloud. We reduced both pulses but later found that the last pulse gave heights more in line with those from the RBC. The last pulse was subsequently used for Ceilograph height analysis. The Ceilograph detector scans continuously from 20 degrees to 89 degrees and back to 20 degrees elevation every minute. The detector head, moved by an off-center spindle, scans at a variable rate with time versus angular elevation linear in logarithms. We determined the time versus angular elevation of up-scans to be:

$$\theta = 20.394 \, (\ t\ )^{.4332} \quad \text{for } 0<t<30 \qquad (2)$$

and the down-scan function:

$$\theta = 20.394 \, (60-t)^{.4332} \quad \text{for } 30<t<60 \qquad (3)$$

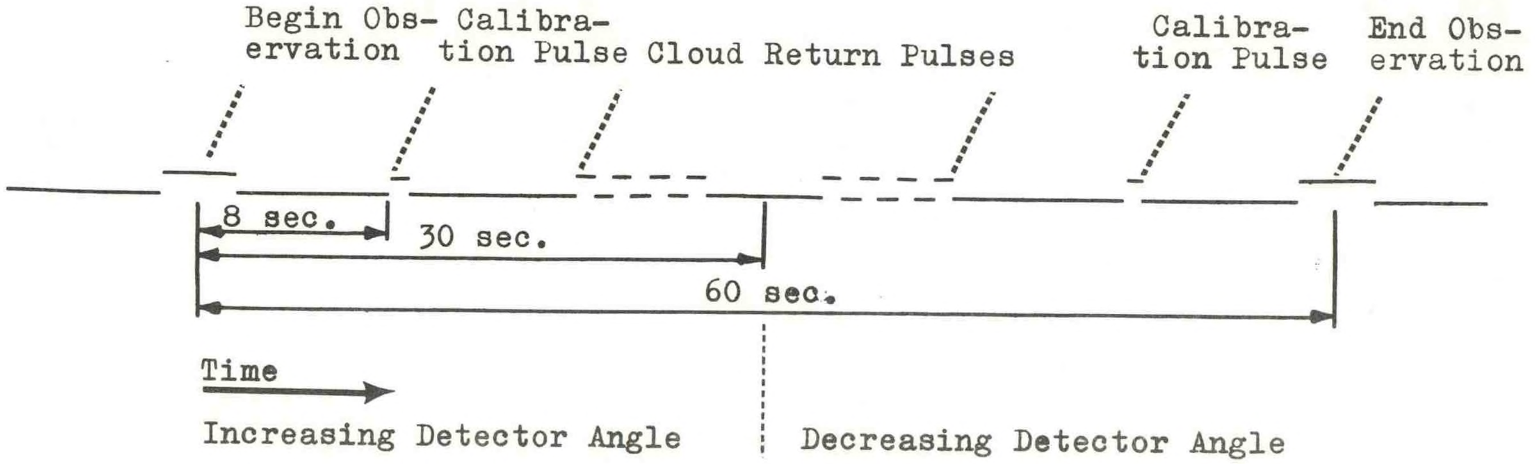


FIGURE 11. Typical Ceilograph Cloud Height Observation

where t is the time of cloud return, in seconds, after the beginning of an observation, and θ is the angular elevation of the return, in degrees.

The altitude corresponding to an elevation angle was found by applying the trigonometric relationship

$$\text{altitude} = 250 \tan \theta \qquad (4)$$

where 250 is the distance between projector and detector in feet.

Laser ceilometer returns were recorded somewhat differently. We displayed laser returns on a storage oscilloscope, then used a Polaroid camera to photograph the still trace. Examples, taken when fog restricted visibility to about one mile, are shown in figure 12, traces a **and b**. The abscissa is in signal transit time, the ordinate in detector voltage gain. When cloud base was indistinct or when precipitation was occurring, it was very difficult to choose a segment of the return trace as an indication of cloud base. We found this true regardless of the experience of the data reducer. We resorted to plotting cloud returns on semi-log graph paper. This made the laser signatures more recognizable, as you see in figure 13, which was drawn from figure 12. Under more ideal conditions, i.e., no fog or precipitation, thick, overcast clouds, signal returns were less difficult to analyze. Interpretation was still required however, as illustrated by figures 12 and 13, trace c.

After examining several plots like those in figure 13, a pattern began to emerge. From the pattern, we were able to devise two criteria which seem to indicate existence of a cloud base: (1) a large increase in back-scattered energy which extends through a layer of 300 feet or more, or (2) a W-shaped backscatter return in which each element of the W is at least 100 feet thick. These criteria were applied to give us a data sample of 116 laser cloud returns.

7.3 Ancillary Information

Auxiliary information used to classify data (except for the laser) was recorded from a photopanel laid out as in figure 14. A 35 mm. camera photographed the panel once each minute. Additional longhand notes were made by data acquisition personnel during each data period.

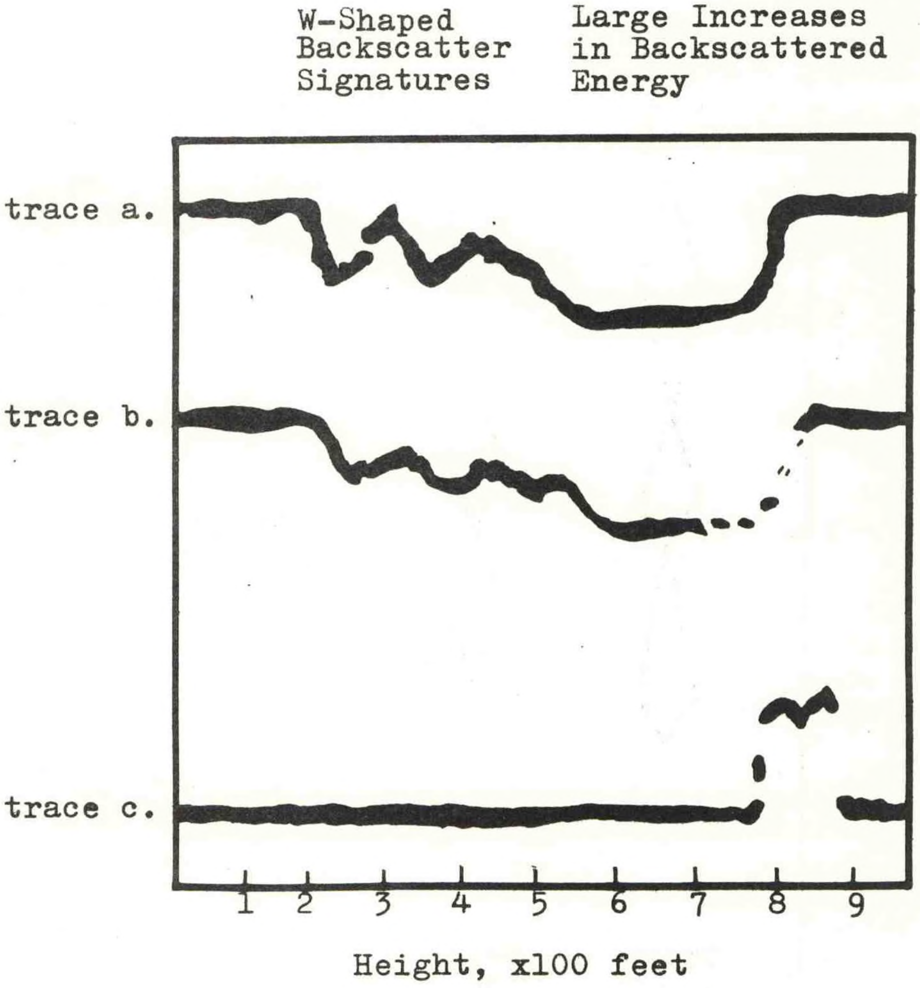


FIGURE 12. Typical Laser Cloud Height Observations

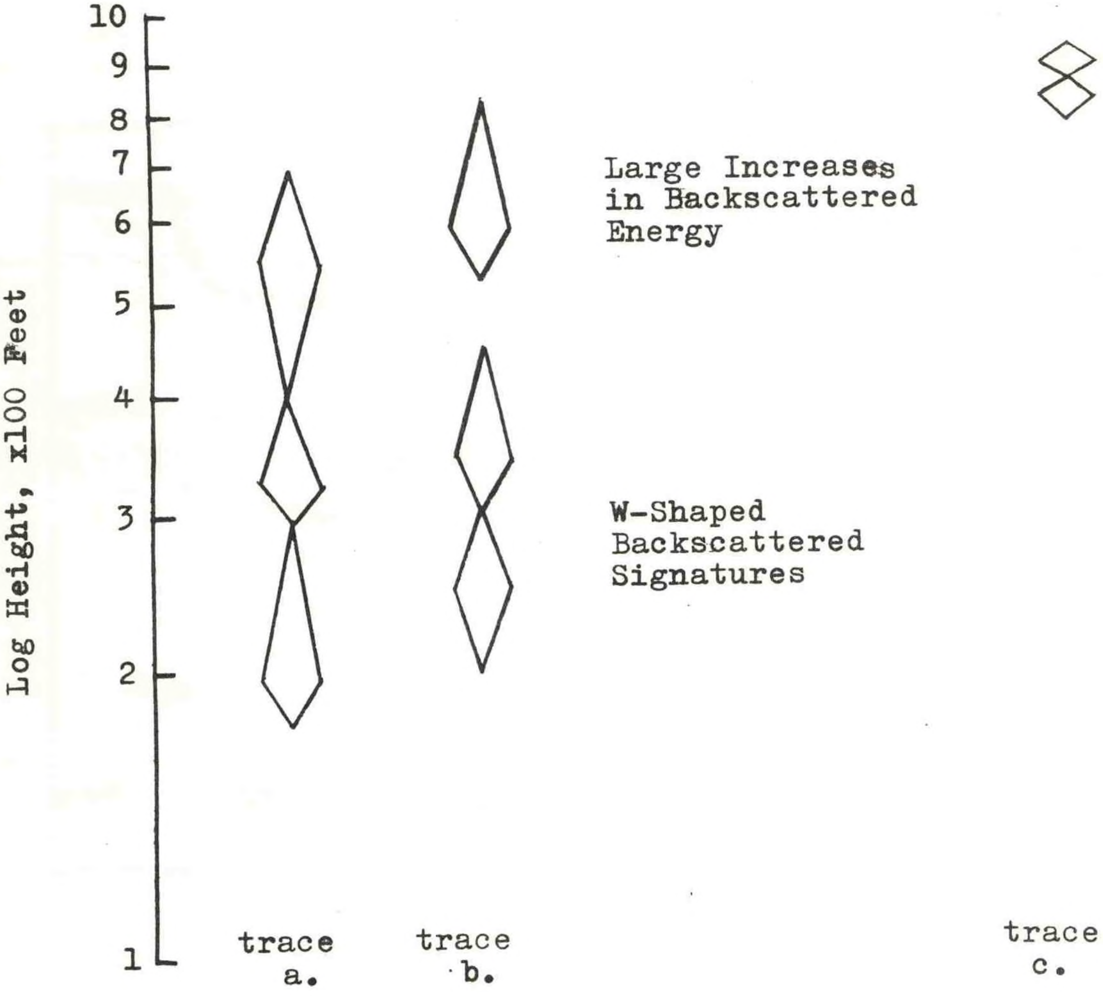
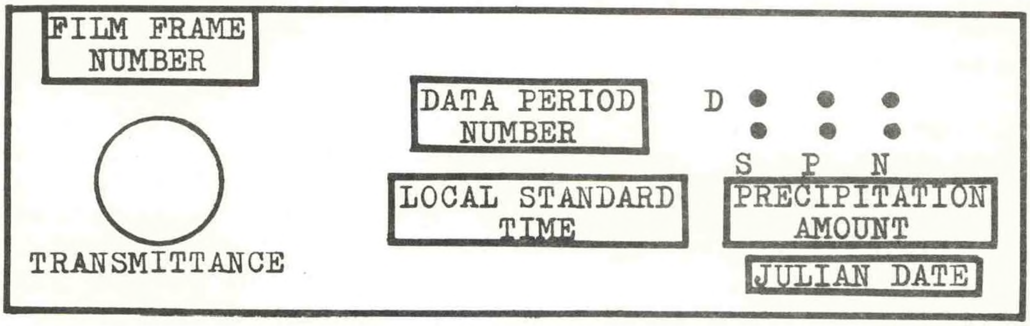


FIGURE 13. Typical Laser Cloud Height Reductions



D - Data lamp. When lit, data was being photographed.

S - Sunshine occurrence lamp

P - Precipitation occurrence lamp

N - Nighttime lamp

FIGURE 14. Ceilometer Study Photopanel Layout

8.0 CLOUD HEIGHT ANALYSIS

Two main considerations dominated our cloud height analysis scheme. The first was integrating or averaging of observations, and the second was the units in which cloud height should be analyzed.

Knowledge recently gained from Monte Carlo simulations [4] indicates that cloud height information may be averaged over from 1 to 10-minute periods with little or no effect upon the determined height. Our experience with averaging indicates this smoothing produces a desirable characteristic of cloud height data since the variation from one observation to the next may exceed one-half the cloud height. One objective, then, of our analysis scheme was to average cloud height information over some suitable time period. For convenience, we initially chose a six-minute integrating time. Later in the study we found ten-minute periods to be equally suitable and to provide nearly identical mean cloud height measures.

A second bit of knowledge from Monte Carlo simulation implies that observation frequencies greater than one per minute provide little improvement in the accuracy of mean cloud height measurements. We noted this as we compared 10-minute periods of RBC measurements made at the rate of ten-per-minute with measurements made at the rate of two-per-minute.

The above comments, regarding data averaging, were followed with the RBC, TNE 1502 and Ceilograph ceilometers. We weren't able to make frequent enough laser observations to be able to effectively average cloud heights. Because of the large number of separate operations involved with laser observations as well as the slow repetition rate (1/min. maximum), we had to settle for more widely time-spaced simultaneous RBC and laser observations.

At the outset, analysis of cloud height seems to involve straight forward statistical procedures applied to linear height values. Experiences of earlier researchers [5], [6], however, led us to question the usefulness of direct height comparison. For one thing, triangulation and non-triangulation ceilometers have different error functions. The magnitude of triangulation ceilometer error is a function of elevation angle and therefore increases with cloud height. On the other hand, the magnitude of non-triangulation ceilometer error is primarily a function of time and is relatively constant with cloud height. When comparing different types of ceilometers in terms of height then, you would also be comparing error functions of varying and unknown magnitude. In fact, this same problem exists when comparing two different triangulation instruments each having a different baseline.

Our solution to this problem is to analyze cloud return elevation angles rather than cloud heights. This of course necessitates the additional step of reducing cloud height from the various instruments to the equivalent elevation angle of our reference ceilometer, the 400-foot baseline RBC. In comparing equivalent baseline elevation angles, we are able to consider both cloud height information and ceilometer error in terms of a common base unit.

8.1 RBC Precision

By precision we mean the agreement between two collocated ceilometers each measuring essentially the same cloud element at essentially the same time. In this case we are using one RBC projector with the two collocated 400-foot baseline detectors: our standard for comparison, D1, and its twin, D2. Since both RBC's operate on a 400-foot baseline, no conversion to equivalent elevation angle is needed. The big problem in comparing the precision of any instrument lies with the measurement standard. In this study, we have a technique for determining an expected precision for our measurement standard-- the 400-foot baseline rotating-beam ceilometer. Since the same rotating projector is used to produce light which is scattered from clouds down to both detectors simultaneously, the differences in cloud height or in cloud elevation angle sensed by D1 and D2 are measures of expected instrument precision. In using the same projector for both detectors, we are producing best case conditions and must realize that if different projectors were used, our derived precision measures would be even larger than those presented here.

Figure 15 shows the frequency of occurrences of differences between D1 and D2 mean elevation angles. As we discussed earlier, each difference is computed from cloud heights determined over 10-minute data periods. It is apparent from the skewed distribution that D2 indicated larger mean elevations than did D1, and that some bias exists in the observations. Figure 16, cumulative frequencies from figure 15, also shows this bias as the middle two-thirds of D1-D2 differences covers from about -1-1/4° to +1/4°, a 1-1/2° range. Middle ranges for other classes of D1-D2 differences are given in table 2.

In engineering applications, the range of ± one standard deviation and the rms error are frequently taken as convenient measures of accuracy. The middle 68% of the differences, which approximates both rms error and ± one standard deviation, fits quite well with this analysis. Using this measure (tabulated in table 2), you find that daytime RBC precision as determined from D1 minus D2 differences is about ±1° for example.

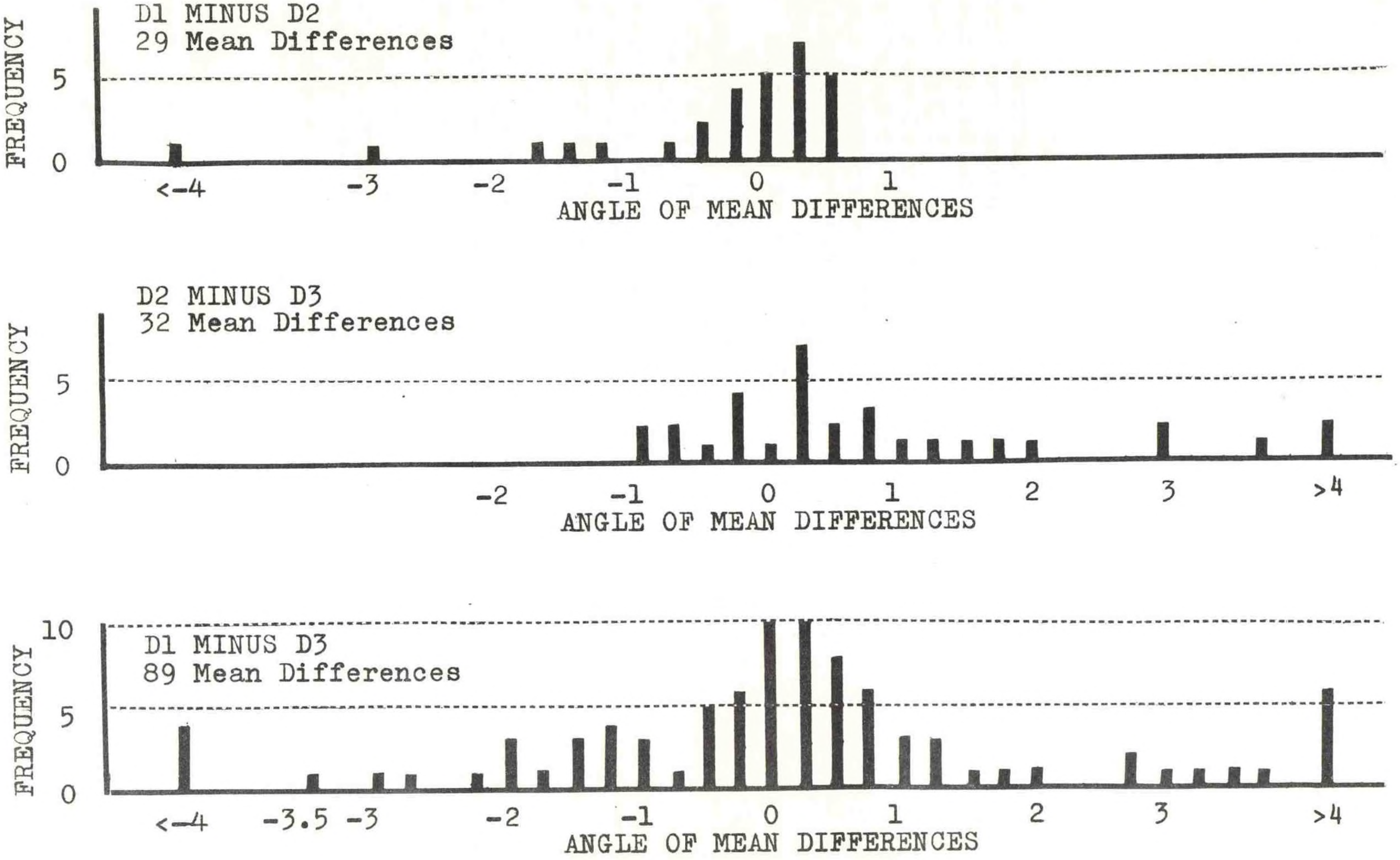


FIGURE 15. Distributions of Mean Cloud Base-Height Differences Converted to Equivalent 400-Foot Baseline Elevation Angles.

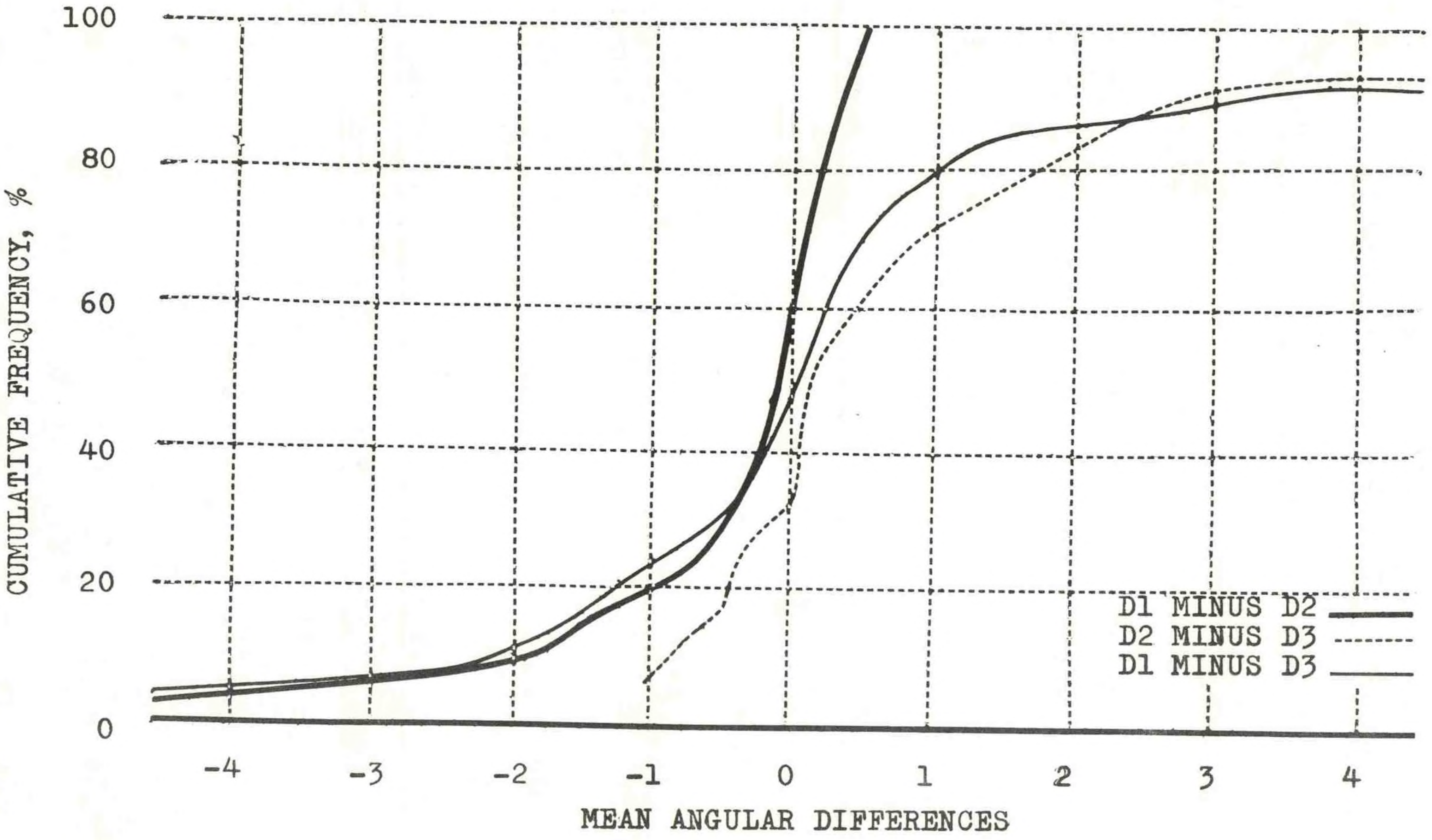


FIGURE 16. Cumulative Frequencies of Mean Cloud Base-Height Differences Converted to Equivalent 400-Foot Baseline Elevation Angles.

TABLE 2

Measures of RBC Precision
Determined From Two 400-Foot Baseline RBC's

ALL DATA	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-1.3°	+0.3°	-1.7°	+0.3°	-1.1°	0°
Precision	±3/4°		±1°		±1/2°	
Median	-0.2°		-0.2°		-0.3°	
No. of 10-Min. Periods in Sample	29		21		8	

PRECIPITATION	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-1.8°	0°	-1.9°	-0.2°		
Precision	±1°		±1°		Too Few Observations For Comparison	
Median	-0.5°		-0.5°			
No. of 10-Min. Periods in Sample	12		11		1	

NO-PRECIPITATION	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-0.9°	+0.3°	-2.7°	+0.4°	-1.2°	+0.1°
Precision	±1/2°		±1-1/2°		±3/4°	
Median	0°		0.1°		-0.3°	
No. of 10-Min. Periods in Sample	17		10		7	

For all data, applying the mid 68% measure of the cumulative frequency, we found the RBC able to deliver cloud height information precise to about ±3/4°. By applying the rule-of-thumb assumption (from the RBC Instruction Manual) of 20% maximum error and our derived ±3/4° precision, the maximum altitude of cloud measurement becomes 86°, or 14 times the baseline. Any error in the recording portion of the RBC would of course add to the ±3/4° accuracy so that the 14 times baseline limit found here would probably drop below the generally accepted value of 10. Likewise, if separate projectors were used, the ±3/4° accuracy range would increase and the 14 times baseline limit would decrease even further below the accepted value.

Table 3 summarizes RBC precision in terms of cloud height rather than elevation angle. Reportable cloud resolution specified by FMH #1 is given for comparison. Based on our study, FMH #1 specifications for cloud height reporting resolution are unrealistic when cloud height exceeds about 1,100 feet and an RBC is used for measurement.

TABLE 3

RBC Precision in Terms of Altitude Versus FMH #1 Reporting Requirements

Cloud Height, Ft.	RBC Precision ± Ft.	(From FMH #1) Reportable Cloud Resolution ± Ft.
100	5	50
500	14	
1,000	38	
1,500	79	
2,000	145	
2,500	211	
3,000	311	
4,000	531	

A measure of RBC central tendency, also taken from the cumulative frequency of D1-D2 angular differences, is the median. Under all conditions, we found the median of D1-D2 differences to be about -.2°. Considering precipitation cases, the median was 0°. There was little difference between daytime and nighttime medians. Daytime was about -.2° and nighttime about -.3°.

Overall then, using the median as a measure of central tendency, you would expect D1-D2 differences to be centered within about 1/4° of zero.

The two measures we have used so far, cumulative frequency for evaluating spread, and the median for evaluating central tendency have been the result of arithmetic computations.

We also tried a graphical check of the precision previously determined. For this graphical approach, we used D3, an 800-foot baseline RBC detector, and determined frequencies of D1-D3 and D2-D3 mean height differences converted to 400-foot baseline elevation angles. Figure 16 shows cumulative frequency curves of D1-D3 and D2-D3. The D2-D3 curve appears to be shifted about 1/4° to 1/2° to the right of the D1-D3. Adjusting D2-D3 1/4° to the left brought the two curves into good agreement between 45% and 70% cumulative frequency. Outside of this range though, D2-D3 was still placed well to the right of D1-D3 curve. Shifting D2-D3 a full 1/2° to the left placed the two curves in good agreement above 70% cumulative frequency and from 25-35% as well. Agreement was not so good however below 25% and from 35% to 70% as may be seen on figure 17. The 1/2° shift does produce overall a more even match between the curves. On this basis, it appears that the difference between curves, (D1-D3) - (D2-D3) = D1-D2, is closer to -1/2° than to -1/4°. Table 4 presents the resulting measures of precision.

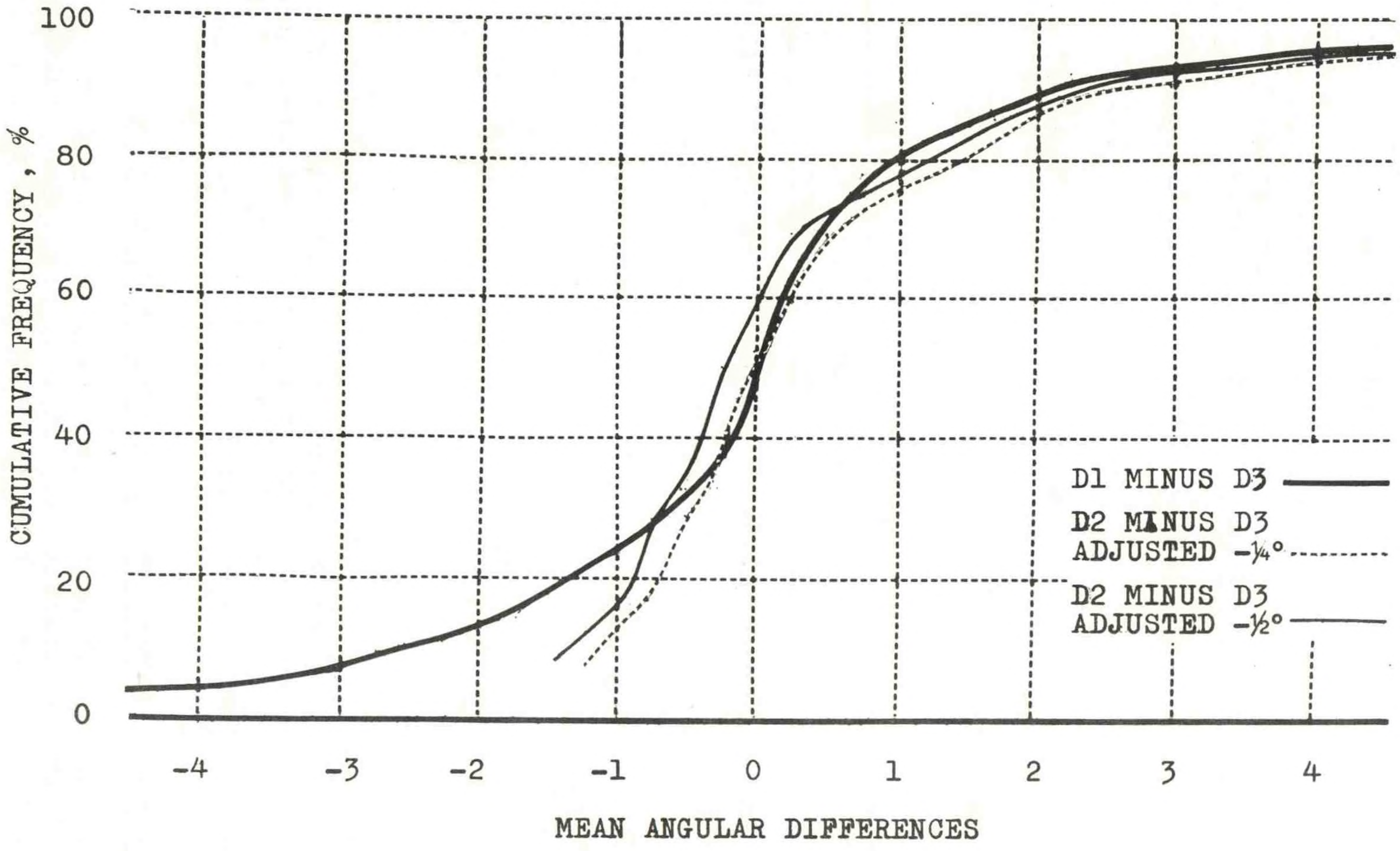


FIGURE 17. Graphical Measures of RBC Precision

TABLE 4

Measures of RBC Precision Determined Graphically From
Two 400-Foot and One 800-Foot Baseline RBC's

	D2 - D3		D2 - D3 Adjusted -1/4°	
ALL DATA	From	To	From	To
Middle 68%	-0.5°	+2.°	-0.8°	+1.8°
Precision	±1/4°		±1-1/4°	
Median	+0.2°		-0.1°	

ALL DATA	D2 - D3		D1 - D3	
	Adjusted -1/2° From	To	From	To
Middle 68%	-1.1°	+1.5°	-1.6°	+1.5°
Precision	±1-1/4°		±1-1/2°	
Median	0.3°		0°	
No. of 10-Min. Periods in Sample	32		89	

In this section, we have developed an overall measure of RBC precision, ±3/4°. RBC precision is therefore not great enough to allow use of the ceilometer for measuring cloud height to the nearest 100 feet, as per FMH #1.

8.2 400-Versus 800-Foot RBC Cloud Height Comparison

Comparing cloud height returns from ceilometers not at the same location involves evaluation of not only precision, but also spatial and time variations in the sampled cloud field. In the

TABLE 5

Measures of Cloud Elevation Angle Differences Found Between 400-Ft. and 800-Ft. Baseline RBC's

ALL DATA	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-1.6°	+1.5°	-1.4°	+1.2°	-1.8°	+2.8°
Difference	±1-1/2°		±1-1/4°		±2-1/4°	
Median	0		0		0	
No. of 10 Min. Periods in Sample	89		67		22	

PRECIPITATION	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-2°	+3°	-2°		-3.5°	+3.7°
Difference	±2-1/2°		±3/4°		±3-1/2°	
Median	-1°		-0.2°		-0.1°	
No. of 10 Min. Periods in Sample	51		38		13	

NO-PRECIPITATION	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-1°	+.8°	-.8°	+.9°	-1.8°	+.7°
Difference	±1°		±1°		±1-1/4°	
Median	-0.1°		-0.1°		-.2°	
No. of 10 Min. Periods in Sample	38		29		9	

case of our 400-foot and 800-foot RBC's, the time difference between 400-and 800-foot observations is negligible, on the order of one second or less. Since we now have a measure of RBC precision and since time variations is near zero, we can evaluate the difference in observed cloud elevation found by detectors which are located 400 feet apart.

Table 5 lists measures of D1-D3 differences for combinations of day/night/precipitation conditions. In all but one case, the middle cumulative frequency range of D1-D3 was greater than that of D1-D2 (table 3). The lone case in which the D1-D2 range exceeded that of D1-D3 was one in which the D1-D2 range was unusually large.

For all D1-D3 data, the middle 68% of the differences was centered near zero and covered a 3° range. This contrasted with the overall RBC precision range of 1-1/2°. In general the differences between mean cloud height elevation angles observed by identical RBC's located 400 feet apart is on the order of 1/2 to 1-1/2 times RBC precision. Night differences are more disperse than those found during daytime periods, and those determined from precipitation periods are greater than differences found when no precipitation was occurring.

Differences attributable to the 400-foot distance between D1 and D3 are listed in table 6. Table 6 is simply a subtraction of table 5 from table 3.

TABLE 6

Difference in Mean Cloud Elevation
Attributable to RBC Location (400 Feet Apart)

ALL DATA

Total	Day	Night
3/4°	1/4°	1-3/4°

PRECIPITATION

Total	Day	Night
1-1/2°	-1/4°	___

NO-PRECIPITATION

Total	Day	Night
1/2°	-1/2°	1/2°

8.3 RBC Versus Ceilograph Height Comparison

Comparison of cloud height response becomes less definitive when different ceilometers observing from different locations at different times are compared. In these circumstances, time, spatial, and instrument variations combine to produce observed cloud height differences which are much greater than those determined by using two identical collocated ceilometers.

Figure 18 shows cumulative frequencies of D1-Ceilograph equivalent elevation angle differences for precipitation cases. The three no-precipitation data periods which occurred during the Ceilograph data acquisition season are omitted here in order to present the precipitation-only case. The three periods do fit well with this data. The nearly linear Day and Total D1-Ceilograph curves indicate that no central tending pattern of elevation angle difference exists. This is in contrast to the D1-D3 precipitation curve also shown in figure 18. There is quite a large difference between day and night cases, though the range of night differences is somewhat smaller, as indicated by table 7. Comparison of the measures in table 7 with those determined from the RBC tables 2 and 5 emphasizes the much greater D1-Ceilograph differences. Apparently the intensity, pulse duration, and wavelength of Ceilograph light as well as detector response causes the Ceilograph to indicate clouds at much lower altitudes than those reported by the RBC.

TABLE 7

RBC Minus Ceilograph Cloud Elevation Difference Measures

PRECIPITATION	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-3-1/2°	17-1/2°	-1/2°	16-1/2°	-9°	21°
Difference	±10-1/2°		±8-1/2°		±15°	
Median	9°		9-1/2°		1°	
No. of 10 Min. Periods in Sample	22		18		6	

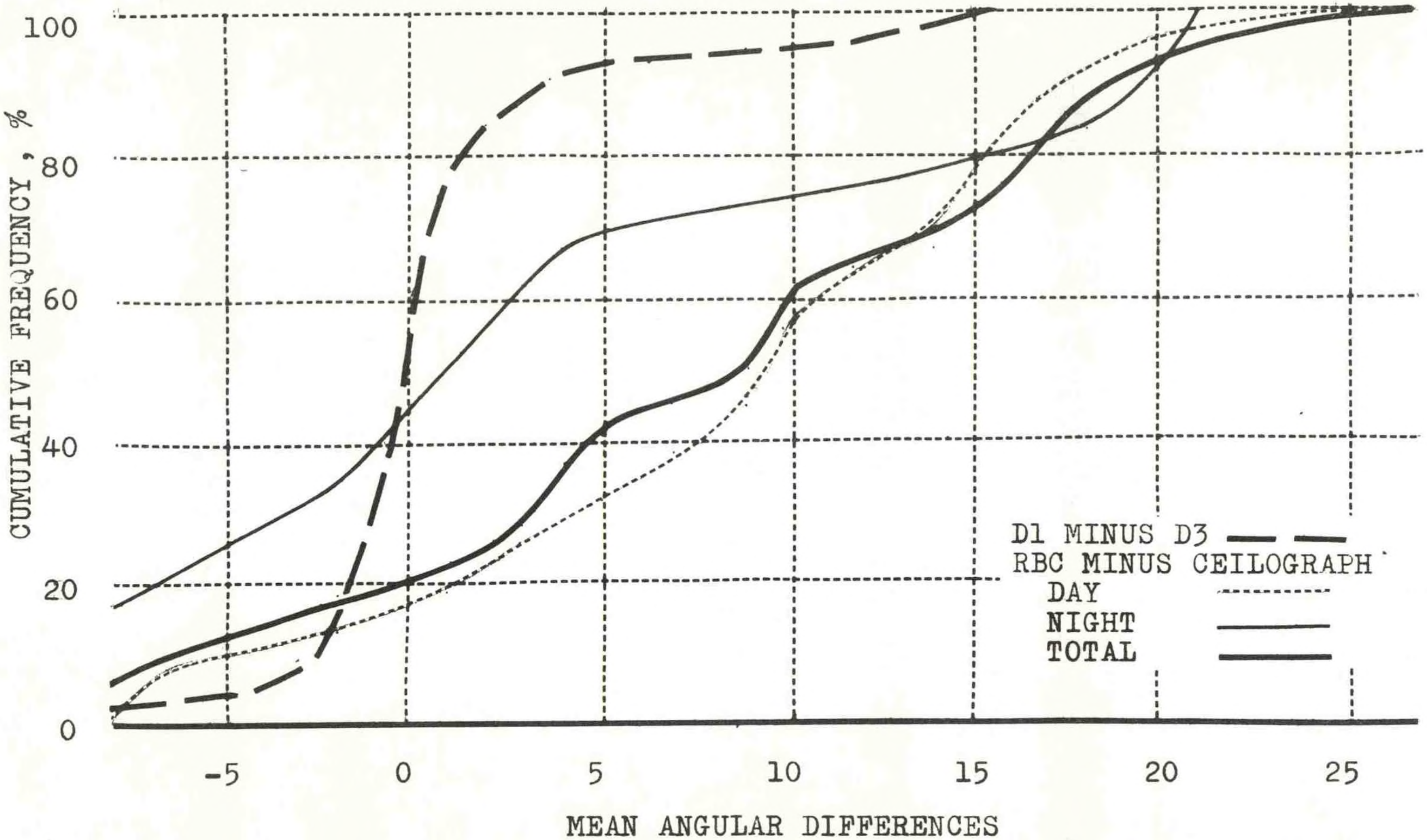


FIGURE 18. Cumulative Frequencies of RBC Minus Ceilograph Equivalent Cloud Elevation Differences - Precipitation Conditions

8.4 RBC Versus Optical Radar Height Comparison

D1 minus TNE 1502 cumulative frequencies are shown in figures 19 and 20. The middle 68% ranges and medians are presented in table 8. In general, nighttime cloud height differences were spread over a wider range than daytime differences. Precipitation differences were less diverse than those observed during no-precipitation conditions.

TABLE 8

RBC Minus TNE 1502 Cloud Elevation Difference Measurements

PRECIPITATION	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-13°	6-1/2°	-7-1/2°	5-1/2°	-21°	15°
Difference	±8-3/4°		±6-1/2°		±18°	
Median	1/2°		0°		4°	
No. of 10 Min. Periods in Sample	37		25		12	

NO-PRECIPITATION	Day	
	From	To
Middle 68%	-19-1/2°	0°
Difference	±9-3/4°	
Median	-1-3/4°	
No. of 10 Min Periods in Sample	15	

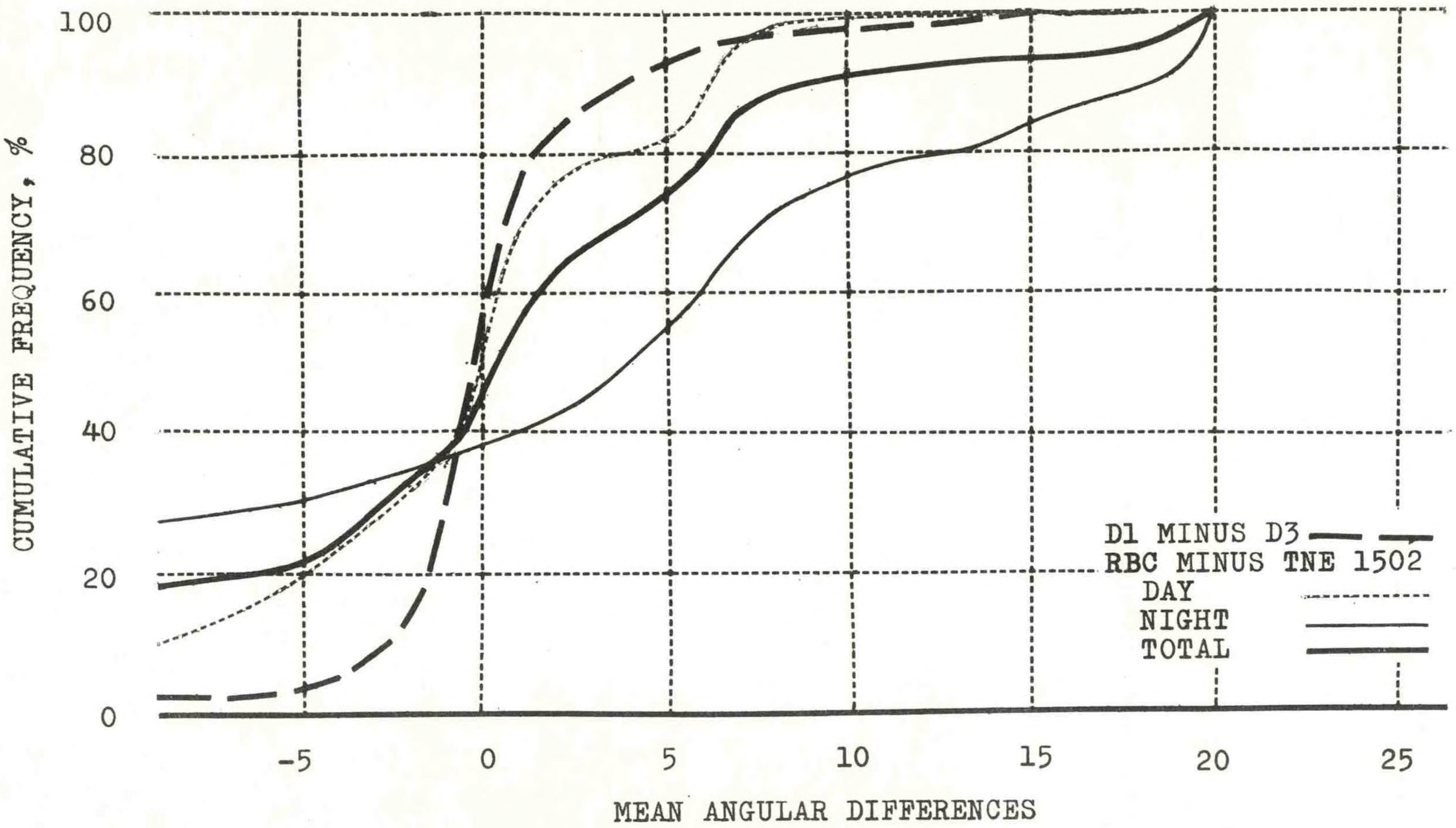


FIGURE 19. Cumulative Frequencies of RBC Minus TNE 1502 Equivalent Cloud Elevation Differences - Precipitation Conditions

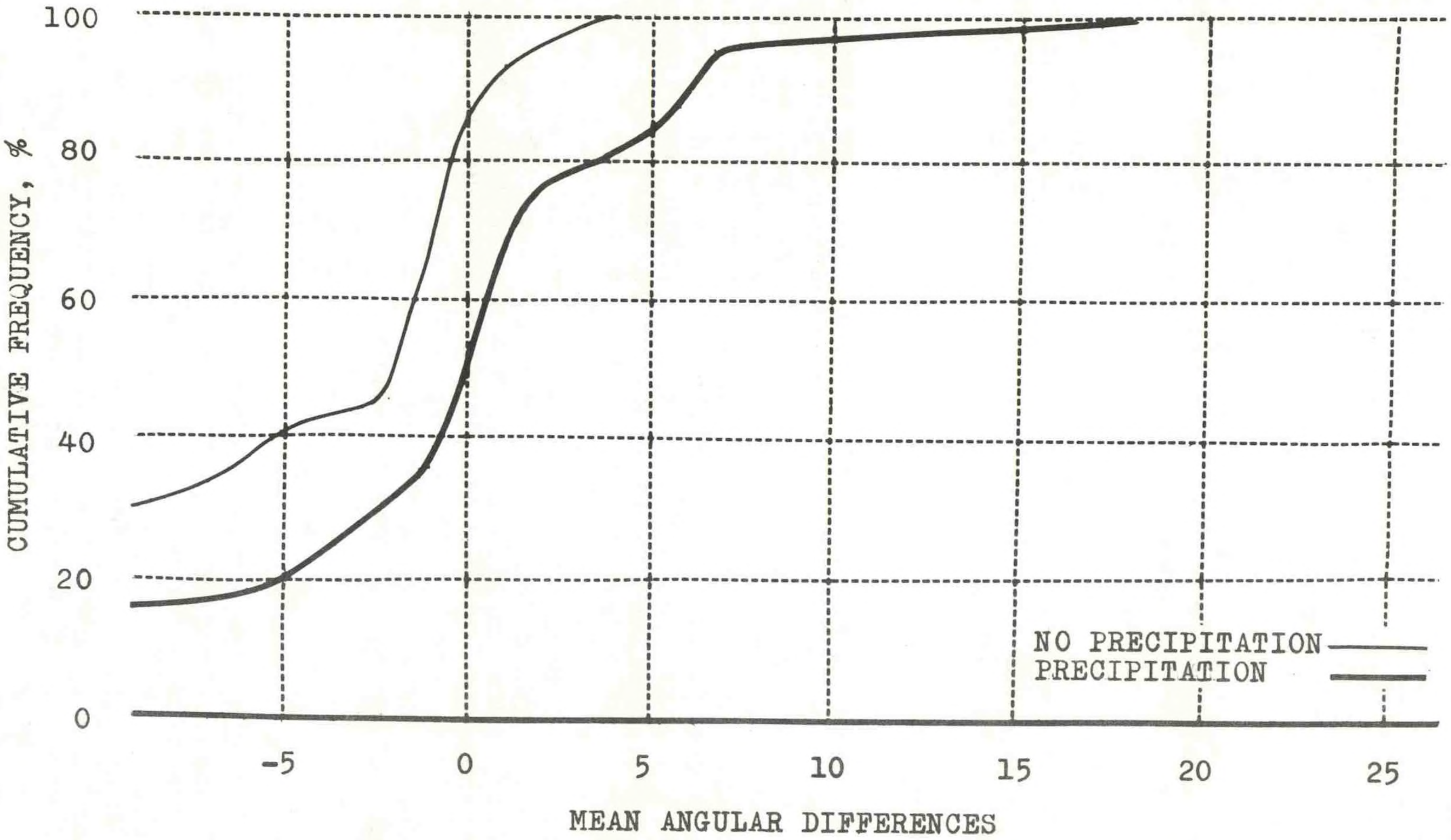


FIGURE 20. Cumulative Frequencies of RBC Minus TNE 1502 Equivalent Cloud Elevation Differences - Daytime Observations

While precipitation differences were centered about 0°, the no-precipitation cases center -2°. We noticed one point, the cumulative frequency curves in figure 20 are similarly shaped and appeared amenable to a graphical analysis. We graphically adjusted the D1-TNE 1502 no-precipitation curve -4° to achieve a good fit. The fit indicates that the optical radar reports cloud elevations to be about 4° lower than the RBC overall, but is in better agreement with the RBC during precipitation occurrences. We believe the optical radar ceases to observe cloud elements when precipitation is falling. Rather, under these conditions the predominant reflection is from the relatively large precipitation particles and the optical radar is simply unable to either detect or distinguish the weak returns from cloud particles. The height recorded would therefore be lower than if no precipitation were occurring and the difference D1-TNE 1502 will tend toward larger positive values as verified by figure 20.

8.5 RBC Versus Modified RBC Precision

The modified RBC with the EDL solid state amplifier appeared to provide more consistent mean cloud elevation angles than did D2 with the standard tube-type amplifier. And, as the summary in table 9 indicates, the solid state amplifier output was more consistent regardless of day/night or precipitation/no-precipitation conditions. The greatest improvement in consistency over the standard amplifier occurred during precipitation conditions, as summarized by figure 21. Inasmuch as the solid state amplifier was an experimental unit, and owing to the small data sample collected, these results must be taken as but indications of performance likely to result from a more thoroughly developed model. It appears, though, from table 9, that the solid state amplifier yields a precision of ±1/2° where the standard amplifier yields ±3/4°. Allowing a 20% error and ±1/2° precision, this raises the upper elevation of RBC measurements to 87° or 19 times the baseline based upon the RBC Instruction Manual rule-of-thumb.

8.6 RBC Versus Laser Ceilometer

Because of the limited sample collected with the laser ceilometer, we chose to compare individual observations rather than 10-minute data periods as we did with the other ceilometers studied. We gathered 116 simultaneous observations from the RBC and the laser ceilometer. The cumulative frequency of RBC minus laser cloud elevation differences are shown in figure 22. Since the laser and RBC detector were about six feet apart, we can consider the middle 68% of RBC minus laser differences to be a measure of laser precision.

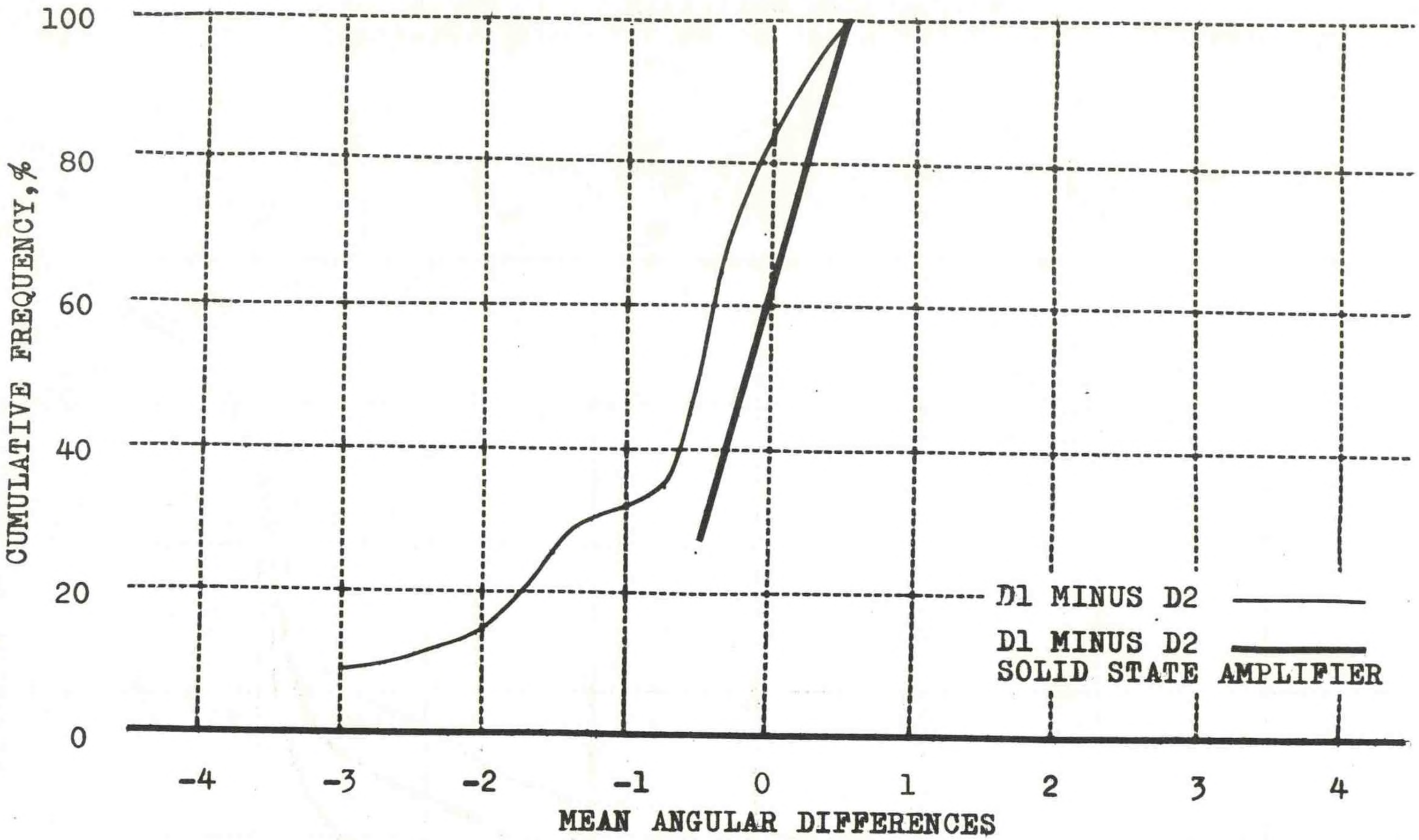


FIGURE 21. Cumulative Frequency of RBC Standard Amplifier Minus Solid State Amplifier Equivalent Cloud Elevation Differences - Precipitation Conditions

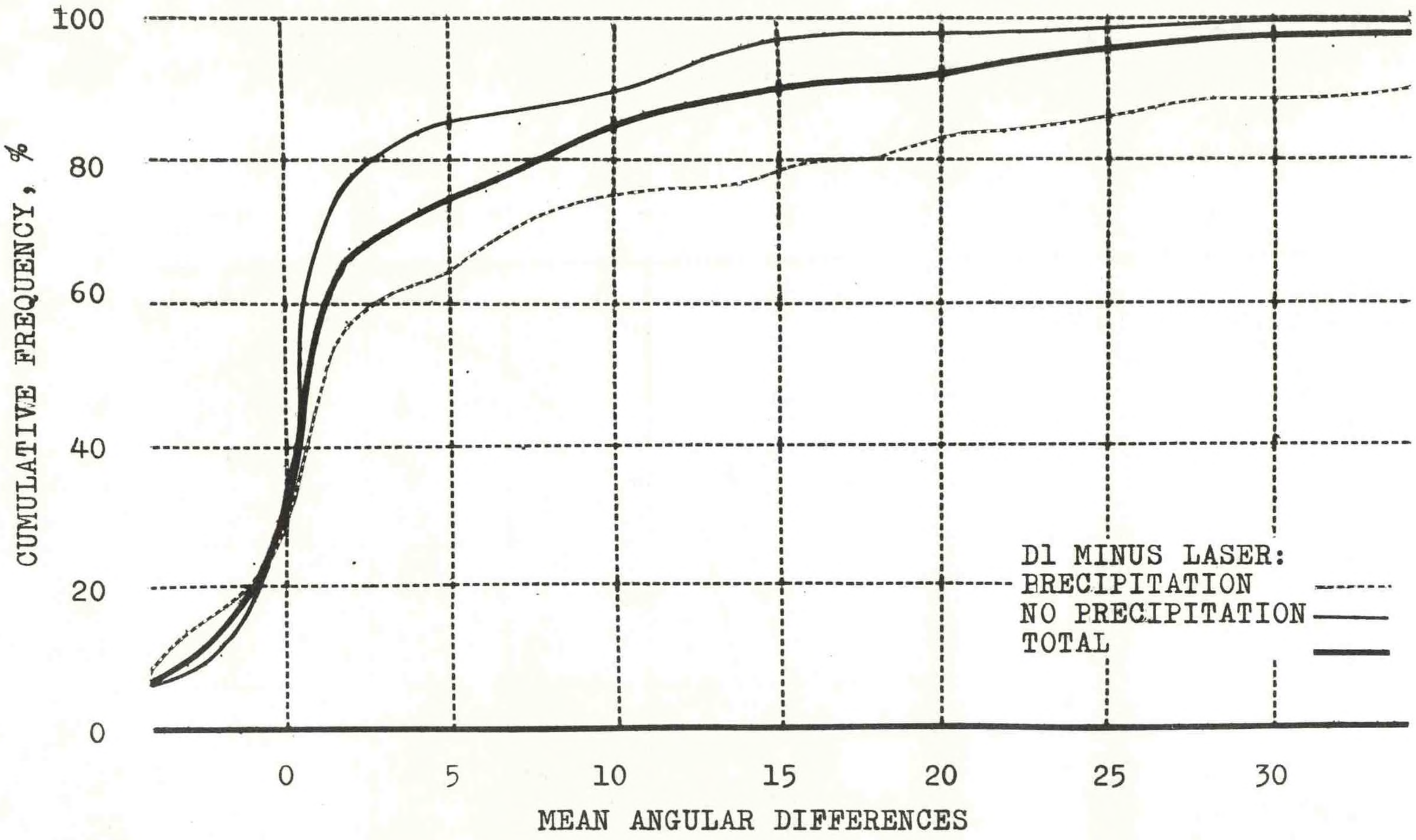


FIGURE 22. Cumulative Frequencies of RBC Minus Laser Ceilometer Equivalent Cloud Elevation Differences

TABLE 9

Measures of RBC Standard Amplifier Minus
Solid State Amplifier Cloud Elevation Differences

ALL DATA	Total		Day		Night	
	From	To	From	To	From	To
Middle 68%	-.7°	.2°	-.7°	.2°		
Median	-0.1°		-0.1°		-0.25°	
No. of 10 Min. Periods in Sample	28		24		4	

	NO-PRECIPITATION		PRECIPITATION	
	Total		Total	
	From	To	From	To
Middle 68%	-.7°	.3°		
Median	-0.1°		-0.2°	
No. of 10 Min. Periods in Sample	18		10	

These are summarized in table 10. These measures are not directly comparable to those found when we used other ceilometers. With the laser we have compared individual observations. With the other ceilometers we were able to compare mean values from 10-minute data periods. The small number of laser comparisons makes for tentative results. We feel that the ±6-1/2° precision figure is but a ball park figure of how well the laser agrees with the RBC.

TABLE 10

Measures of Laser Ceilometer Precision
Determined From Simultaneous Observations

	Total		Precipitation		No Precipitation	
	From	To	From	To	From	To
Middle 68%	-1-1/2°	11-1/2°	-2°	15-1/2°	-1°	6°
Precision		±6-1/2°	±9°			±3-1/2°
Median		1/2°	1-1/4°			1/4°
No. of 10 Min. Periods in Sample		116	59			57

8.7 Response Through Precipitation and Fog

On occasion, during heavy precipitation, the RBC was unable to output cloud height. This failure was common also when visibility was severely restricted by fog. Characteristically, the signal amplifier became saturated as the lamp began its upward rotation. Though signal return intensity decreased (tapered) with increasing lamp elevation angle, the rate of change was frequently too small to enable cloud height evaluation. It appeared that the light beam penetrated deeply into the obscuration and was attenuated to the extent that no signal envelope was received. While there was no quantitative height output, this response may be an indication that vertical visibility was being measured rather than the height of an atmospheric discontinuity, such as a change in water content or drop size near a cloud base. Unfortunately, we did not find this relationship between atmospheric transmittance and the height at which the tapered signal ended. Much of this result stems from the use of modulated light. The resulting sinewave output does not present an unambiguous, definite point which can be considered for an evaluation of vertical visibility, as is suggested by FMH #1. We had similar experiences with the Ceilograph. During heavy rain or heavy fog, the Ceilograph output is a continuous sequence of pulses. The pulse train, composed of uniform amplitude and duration pulses, and having a definite ending point, allowed for evaluation of the limit of vertical visibility. As with the RBC, the height or number of pulses did not seem related to atmospheric transmittance.

The optical radar on the other hand, responded quite differently during fog and precipitation conditions. It seemed as if optical radar light penetrated through obscuring phenomena to the cloud base. And in general, during fog conditions the optical radar reported cloud heights at greater altitude than did the RBC. Table 11 presents a listing of mean heights from 8 data periods. As you see, the optical radar reported consistently greater heights.

TABLE 11

RBC and Optical Radar Mean Cloud Heights Reported Through Fog

RBC	Optical Radar	RBC	Optical Radar
1,730 ft.	2,125 ft.	707 ft.	1,286 ft.
1,044	1,146	631	1,156
888	1,050	375	814
720	933	146	4,058

Another optical radar characteristic is shown by the RBC versus TNE 1502 cloud height scattergram, figure 23. With precipitation falling, and for RBC cloud heights less than 1,000 feet, there appears a tendency for the optical radar to report greater cloud heights than the RBC. This relationship reversed and became more obvious however, as RBC reported heights exceeded about 2,500 feet. In the range 1,000 to 2,500 feet, the optical radar and RBC agreed fairly well.

Possibly of greater importance is the fact that the optical radar reported cloud information during data periods when the RBC reported no definable cloud elements. We found that the optical radar reported cloud heights during all 14 of the data periods when snow was falling. The RBC on the other hand, failed to report cloud heights on 4 of the 14 occasions. Similarily during fog periods, the RBC reported cloud heights on 32 of 39 occasions while the optical radar reported cloud heights during all 39 periods. Though the optical radar technique might tend to overstate vertical visibility under fog conditions and thus create a potential hazard to airport operations, its ability to penetrate obscuring phenomena

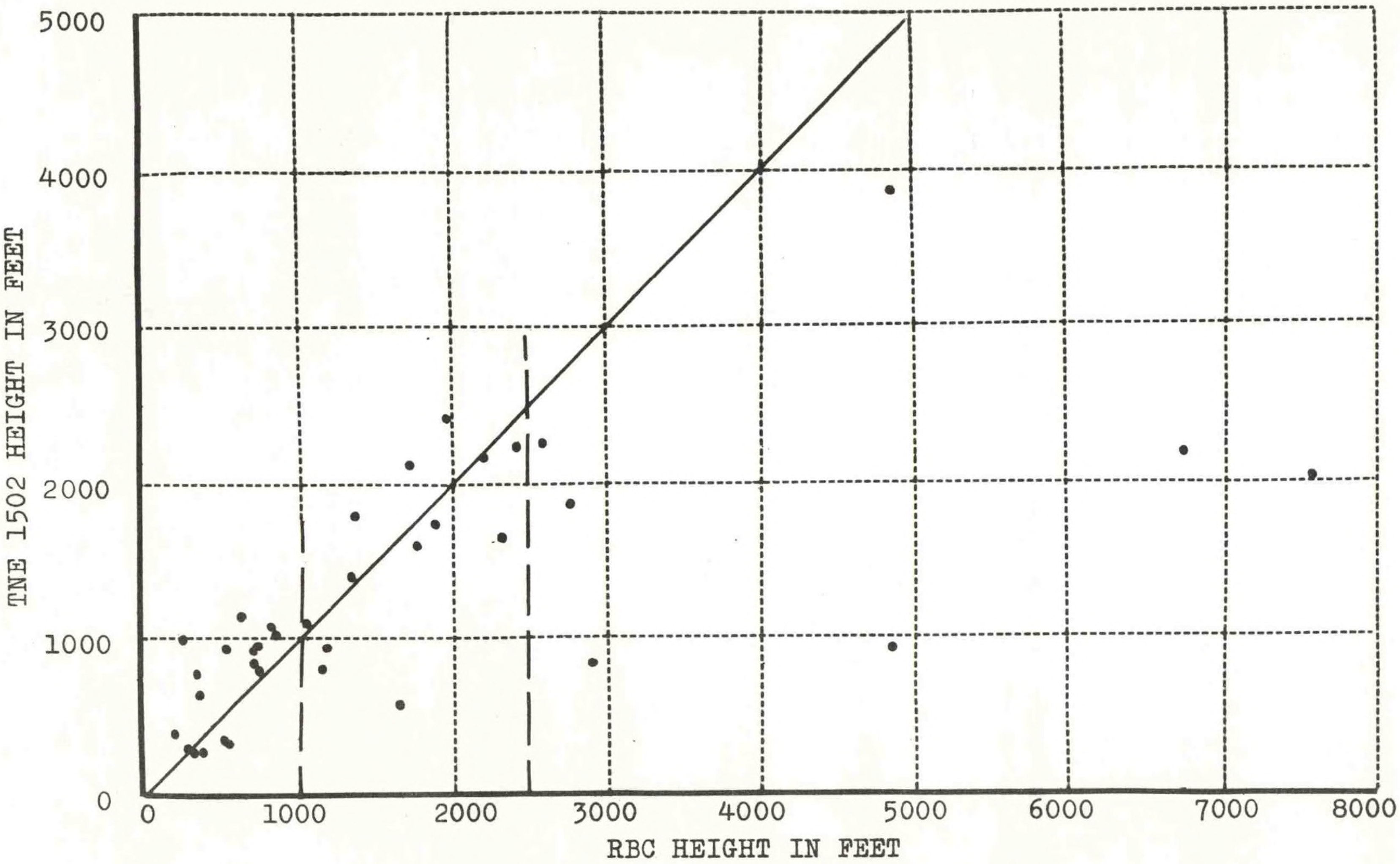


FIGURE 23. Scattergram of RBC Versus TNE 1502 Cloud Heights During Precipitation

would be beneficial at remote or enroute locations where the presence of cloud elements is important input to the forecast system.

8.8 Response to Extraneous Signals

Along with comparing each ceilometer's cloud height response, we also investigated each system's response to extraneous signals. RBC responsiveness to noise has long been considered a drawback to the system. One of the first effects we investigated was ceilometer response to scattered Strobecon light. A row of from 6 to 28 Strobecon lamps are frequently placed at the approach end of the airport runway near and parallel to the ceilometer baseline. Used as a landing aid during low visibility, the high intensity (3 x 10^7 candela peak) pulsed Xenon lights are reflected from cloud bases and received by the ceilometer detector. In our study we had to settle for a single Strobecon lamp rather than a row of lamps. The single lamp was portable and could be placed very near the RBC detector, however. It produced interference, but the frequency was much less than that encountered from a row of lamps at an airport runway environment. Example RBC responses are shown in figure 24. Typically, the noise builds up to a peak in one or two cycles, then decays for three to five cycles. The total response covers about 1/25 second. A row of these lamps, flashing in sequence twice per second, will produce a nearly continuous level of noise which can completely mask any indication of cloud height.

Strobecon interference was slightly reduced by orienting the beam perpendicular to the RBC detector. Because of Strobecon beam divergence, reorientation of RBC baseline and Strobecon lamps may produce no significant reduction in interference.

We found the rotating-beam ceilometer to be sensitive to mechanical vibration as well. Aircraft flying overhead or trucks driving nearby cause the detector to output signals which resemble those received during low visibility conditions. Frequently, vibration completely saturates the RBC amplifier thus making cloud height measurement extremely difficult during the day.

We also looked into what is called the refraction phenomenon. The phenomenon, actually a combination of both refraction and internal reflection of light from waterdrops, was researched optically many years ago [7]. The occurrence was fairly common with the old Weather Bureau fixed-beam ceilometer under conditions of light, steady rain. In fact numerous references to fixed-beam refraction are still contained in FMH #1, while none are shown for the RBC. The interference, which appears as a constant altitude cloud return, is a function of wavelength.

For the rotating-beam ceilometer, primary refraction occurs at about 45° elevation angle with a secondary refraction possible at about 44°. Though we noted several occasions of primary RBC refraction, signal to noise was quite low, on the order of 1.5:1 while signal to noise for cloud returns averaged over 3:1. The refraction phenomenon therefore poses no problem nor should it be a hindrance to automation of RBC cloud height information.

Ceilograph response to extraneous signals was an improvement over that of the RBC. The Ceilograph was totally insensitive to vibration from overflying aircraft and nearby surface traffic as well as stray sunlight. In addition, refraction phenomena, expected at about 47° elevation with the Ceilograph, were not observed. The Ceilograph was, however, quite sensitive to Strobecon interference. In all cases, the Ceilograph output a cloud indication coincident with each pulse of the Xenon Strobecon lamp (see figure 24). Even with modified circuitry, we are not certain that the Ceilograph could discriminate between its own Xenon light flash and those from a long string of sequentially flashing Strobecon Xenon lamps common to an airport environment.

The optical radar was insensitive to all types of interference investigated. Refraction is no problem since triangulation principles are not used. We never observed vibration, Strobecon, or sunlight interference on the system. The optical radar is clearly superior to the RBC and Ceilograph in this respect.

The modified RBC with a solid state amplifier exhibited behavior similar to that of the standard RBC, though the intensity of interference was reduced and the solid state unit seldom became saturated with strong noise. Because of time limitations, we did not formally investigate laser noise response. We did not observe noise interference from vibration or other sources, however.

8.9 Signal/Noise

The standard tube-type RBC amplifier operated during our study at signal to noise ratios of from 1.5:1 up to 14:1. Generally, though, signal/noise was near 6:1. Vibration noise frequently saturated the amplifier as did scattered sunlight during daylight hours. Under these conditions there was no cloud return signal. Similarly, with surface based obscurations, such as fog, the RBC did not receive cloud return signals. It was rare, however, for the RBC amplifier to saturate when a tapered fog return occurred. During Strobecon interference, though, the Strobecon noise itself frequently exceeded the signal level by a factor of 2. Such an example was shown earlier in figure 24.

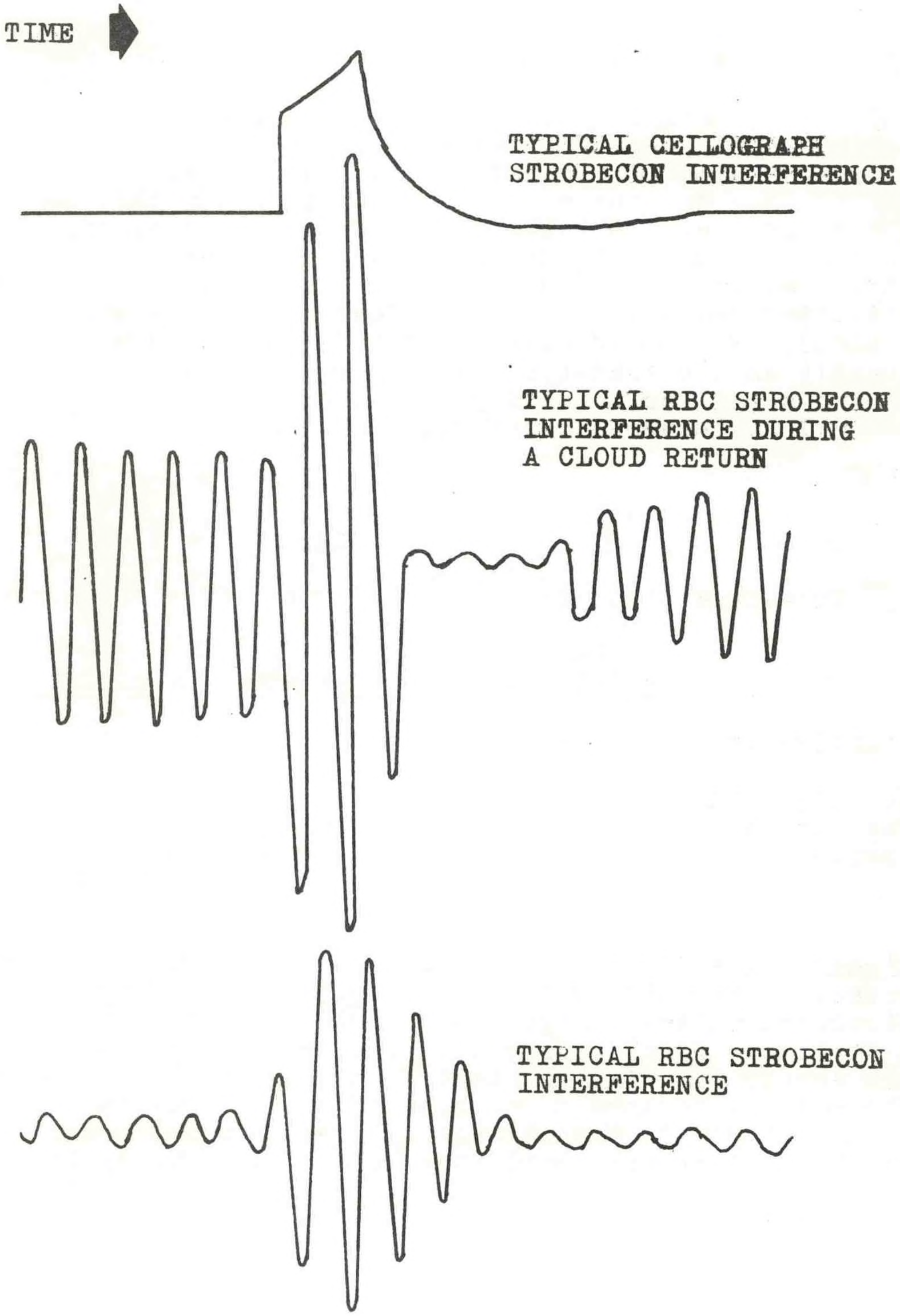


FIGURE 24. Simultaneously Observed Strobecon Interference Patterns

The EDL experimental solid state amplifier operated at about the same signal/noise ratio as did the standard tube-type RBC amplifier under fog conditions and during periods of Strobecon interference. During precipitation periods, the experimental amplifier produced signal to noise 21% greater than the standard amplifier. And the solid state unit output 14% lower signal/noise under no-precipitation conditions. These figures, summarized in table 12, do not completely cover solid state amplifier performance, however. A main advantage of the experimental amplifier results from its performance during high noise conditions. The solid state unit did not become saturated as frequently as the tube-type amplifier. This was evident when comparing signal/noise during less than overcast daytime conditions as well as occurrences of overflying aircraft.

TABLE 12

Tube-Type Minus Solid State RBC Amplifier Signal/Noise

	No Precipitation	Precipitation	Fog	Strobecon Interference
Signal/Noise	14%	-21%	3%	3%
No. of 10 Min. Periods in Sample	15	22	17	21

Signal/noise did not exist with the TNE 1502 as no noise was detected with the system. The Ceilograph, however, did detect Strobecon noise. A typical example was presented in figure 24. A Strobecon flash caused the Ceilograph to output a pulse which was nearly identical to that from a legitimate cloud return. The only difference being that true cloud return pulses were always of constant amplitude, whereas the Strobecon return pulse exhibited increased amplitude before it abruptly began to decay.

9.0 AUTOMATION ANALYSIS

We have evaluated the automatability of each of the four ceilometers. Subjective analysis is reported here as we have no firm basis for an objective assessment. We considered such aspects as the need for and ease of signal interpretation, potential for digitizing cloud return output, susceptibility to noise and vibration, ease of installation, the frequency and importance of maintenance (except for cover glass cleaning), the number and type of internal checks and the ease with which checks may be added.

The rotating-beam ceilometer in its present form is but a fair to poor candidate for automated operation. The RBC lead sulfide photocell displays a temperature dependent noise function which makes the cell virtually unusable at temperatures above 120°F. inside the RBC. In addition, photocell resistance, which determines sensitivity, decreases rapidly with increasing background light so that the cell becomes quite insensitive to cloud reflected light during daytime conditions.

The a-c wave train, in which amplitude is a function of signal strength, requires filtering and interpretation and is difficult to digitize. Any interference, such as from stray airport lights, sunlight, or even nearby aircraft, greatly raises the signal amplitude. In an automated mode there would be little opportunity to distinguish between a cloud return and noise. Though peak discrimination and signal recognition techniques may be useful in some circumstances, the majority of inadequacies would remain. While the RBC gives good cloud height information under optimum conditions (thick clouds, at nighttime, no nearby vibration sources), the system gives information which can be misinterpreted in a totally automated system.

The Ceilograph appears to be a good candidate for automation. Its modern solid state components and reliable Xenon flash lamp make possible long periods of unattended operation. Though biweekly cleaning of cover glasses, mirrors, and lenses will require regular attention, other maintenance is minimal. The constant amplitude Ceilograph output pulses are easily detected in a binary mode. In addition, the synchronization check pulse emitting from the detector amplifier is ready-made for automated operation.

The TNE 1502 is a poor candidate for automated operation. The drawback to the TNE 1502 is the frequency of critically important maintenance. In particular, the two tungsten electrodes which produce the ceilometer light require at least twice weekly maintenance when the system is operated continuously.

The optical radar technique as used by the TNE 1502, however, is a good candidate for automated operation. Its constant amplitude output is easily adaptable to digitizing. For example, the first light pulse could start a counter which would be stopped upon two or three successive cloud indications. The counter could be made to count in direct relation to cloud base altitude, i.e., the higher the first pulse, the more pulses needed to indicate cloud base. Further, the frequent calibration checks made by the TNE 1502 optical radar provide the opportunity to remotely and automatically verify ceilometer operation.

At present, the laser appears to have a fair potential for automated operation. The main drawback to the laser is identical to that of the RBC. The cloud return trace must be interpreted in order to determine cloud base. The logic needed to interpret return traces would be both complex and expensive, and would likely not be able to cover all possible situations. The ASEA laser had no self-checking features though these could be developed rather easily.

10.0 OBSERVATION RATE ANALYSIS

We investigated briefly the effect of observation frequency on mean 10-minute cloud height. To do this, we computed two mean cloud elevation angles for each of 56 data periods. For the first mean, we used each RBC scan. The second mean was found by using every fifth scan. Mean cloud elevations from the two scan rates, 10/minute and 2/minute respectfully, were quite close. In fact, we found the average 10-minute cloud elevation was only 1/4° greater using the 2/minute observation rate. This extends the theoretically based prediction made by Duda that there is little improvement in mean cloud height accuracy when the observation rate is increased above 1 per minute.

TABLE 13

Effect of Observation Frequency Upon
Mean Ten-Minute Cloud Height

	10/Min.	2/Min.
MEAN HEIGHT	839 ft.	835 ft.
MEAN ELEVATION ANGLE	64.50°	64.38°

11.0 SUMMARY OF RESULTS

(1) The rotating-beam ceilometer is precise to ±3/4° elevation. Thus, excluding recorder error, the RBC can realistically report cloud height to FMH #1 specifications (nearest 100 feet for clouds below 5,000 feet) up to only 1,100 feet altitude.

(2) Two RBC's located 400 feet apart reported two-thirds of the mean cloud base heights to be within ±1-1/2°. Thus, a 400-foot change in observation location creates observed cloud height differences of the same magnitude as RBC precision.

(3) The solid state amplifier improved RBC response to cloud returns during optimum conditions and reduced maintenance but it would not greatly improve overall RBC automation potential.

(4) Using 10-minute averaging periods, decreasing observation rate from ten per minute to twice per minute produced little change in reported mean cloud height.

(5) Techniques (modulated and pulsed light) used to develop and process cloud height information are more important than the principles of operation (triangulation and ranging) used by a ceilometer to make the measurements. In particular, pulsed light techniques are superior to modulation techniques regardless of whether ranging or triangulation methods of observation are used.

(6) We have ranked the four ceilometers on the basis of six major factors and twelve minor order factors. The RBC earned the most consistent ranking while the ASEA laser was not completely evaluated due to the short time we had the ceilometer. The TNE 1502 would have ranked higher were it not for frequent, critical required maintenance. Overall, then, the Ceilograph pulsed-light triangulation-type ceilometer is the superior instrument.

TABLE 14

SUMMARY OF CEILOMETER RANKINGS

	Ceilograph	TNE 1502	RBC	Laser
Ease of Installation	2	3	4	1
Maintenance	2	4	3	1
a. Low Frequency	2	3*	3*	1
b. Easy to Perform	2	3	4	1
c. Non-Critical	1	4	3	2
Cloud Height Performance	2	1	3*	3*
a. In Fog	3	1	4	2
b. In Precipitation	2*	1	2*	4
c. Ideal Conditions	1*	1*	1*	1*
Lack of Noise Response	2	1	3	Incomplete Information
a. Strobecon	2*	1	2*	
b. Sunlight	1*	1*	3	
c. Vibration	1*	1*	3	
d. Refraction	1*	1*	3	
Internal Checks	2	1	3	4
a. Included	2	1	3	4
b. Ease of Adding	1*	1*	3*	3*
Ease of Automating	1*	1*	3	4

1: Most agreement with statement
4: Least agreement with statement

* Nearly identical rankings

REFERENCES

1. NOAA-National Weather Service Instruction Manual: Rotating-Beam Ceilometer System, May 1967, 96 pp.

2. NOAA-National Weather Service Federal Meteorological Handbook #1, Surface Observations, U.S. Government Printing Office, Washington, D. C., Jan. 1970, 370 pp.

3. Moroz, Gene, Air Force Cambridge Research Laboratory, Bedford, Mass., June 1971 (telephone conversation).

4. Duda, R. O., Mancuso, R. L., and Blackmer, R. H., Jr., "Theoretical Considerations for Describing the State of the Sky Through Automatic Techniques," Final Report No. FAA-RD-70-13 to National Weather Service and Federal Aviation Administration, May 1970, 169 pp.

5. Morton, W. C., and Haig, T. O., "Variations of Atmospheric Transmissivity and Cloud Height at Newark, "Air Force Survey in Geophysics, No. 91, AFCRC-TN-57-613, Air Force Cambridge Research Laboratory, Bedford, Mass., Jan. 1958, 32 pp.

6. Atkins, E. W., and Hoehne, W. E., "Final Report - The AMOS V Observers Aid Test: Part I, Weather Bureau Technical Memorandum WBTM T&EL 6, Sterling, Va., Oct. 1968, 12 pp.

7. Humphreys, W. J., Physics of the Air, McGraw-Hill Book Company, Inc., New York, 1929, 654 pp.

(From inside front cover)

NWS T&EL	11	Discussion of Sensor Equivalent Visibility. Staff, Observation Techniques Development and Test Branch, July 1971. (COM-71-00964)
NWS T&EL	12	Standardized Functional Tests. Walter E. Hoehne, December 1971.