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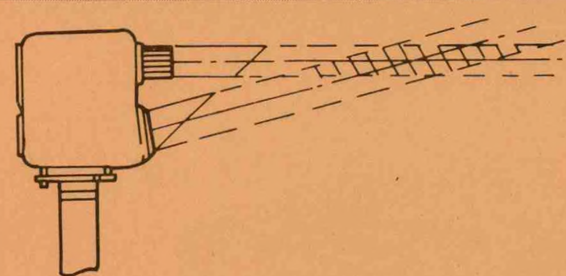
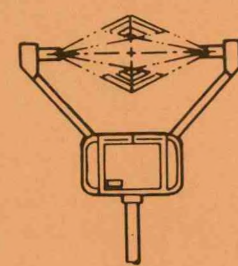
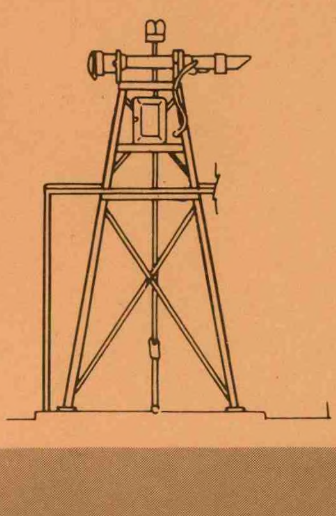




AN OVERVIEW OF

APPLIED VISIBILITY FUNDAMENTALS

SURVEY & SYNTHESIS OF VISIBILITY LITERATURE



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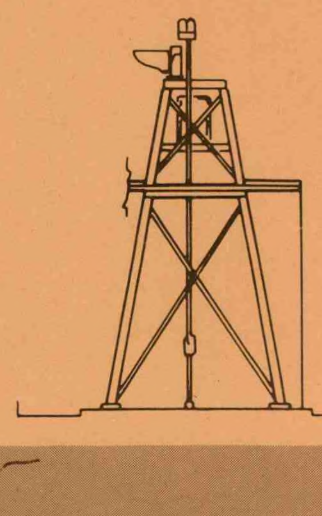

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AN OVERVIEW OF

APPLIED VISIBILITY FUNDAMENTALS

SURVEY & SYNTHESIS OF VISIBILITY LITERATURE

Prepared Under The Auspices Of:

WORKING GROUP ON AUTOMATED SURFACE OBSERVATIONS
SUBCOMMITTEE ON SYSTEMS DEVELOPMENT

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PREFACE -

This report is intended to provide a comprehensive overview of the nature and fundamental concepts of visibility. It has been written for a professional readership that requires general familiarization rather than detailed technical information. As a result, the effort involved in compiling this report consisted primarily of assembling, reviewing, and synthesizing; no original experimentation was conducted, nor are new data presented.

The report is organized into three parts. An executive summary provides a condensation of the most important information contained in the report. The body of the report follows, consisting of eight major sections covering performance of both human and instrument visibility observations. Finally, the appendices contain a technical glossary and bibliographic material, including an extensive annotated bibliography of those materials that made a direct contribution to the report.

The survey was accomplished by Matthew Lefkowitz under guidance provided by an interagency technical oversight committee composed of Dr. Don Acheson, NWS, Advanced Systems Laboratory; Eric Mandel, FAA, Systems Research and Development Service; Gene Moroz, USAF, Air Force Geophysics Laboratory; Dick Reynolds, NWS, Advanced Systems Laboratory; and Charles Douglas.

In addition, specific technical assistance was provided by Dr. Dave Burnham, DOT, Transportation Systems Center; Dr. Jim Bradley, NWS, Test and Evaluation Division; and Ernie Schlaeter, FAA Technical Center.

William S. Barney
Federal Coordinator for
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Supporting Research

EXECUTIVE SUMMARY

1. INTRODUCTION

The concept of visibility has been defined in numerous ways. One source that is widely used in the United States describes visibility as the greatest distance at which it is just possible to see and identify selected objects or light sources with the unaided eye. Put in simpler terms, visibility may be considered the distance an observer would have to back away from a target before it disappears.

The process by which we see distant objects is based on the characteristics of the target, its immediate surroundings, air quality, illumination of the sight path, and the eyes and brain of the observer. Thus, four components of visibility have been noted: (1) target, (2) background, (3) atmosphere, and (4) observer. Most definitions of visibility include the observer as a key element, but it is also possible to measure visibility without the immediate presence of humans by means of instruments such as telephotometers, transmissometers, or nephelometers. Such measurements can be kept in non-dimensional terms and can be compared without human intervention. When used in the field, however, visibility sensors must be calibrated in human terms of visibility measurement. As stated by Neuberger, "The act of seeing is, fundamentally, contingent upon the presence of a brightness contrast." A good example of this effect would be a bright, sunny day in the Arctic region; white objects will seem to disappear in front of the white background of snow, even though the air is very clear.

For daylight conditions, Koschmeider expressed the relationship between contrast and "transmissivity"--a dimensionless number that varies between zero (for an opaque atmosphere) and one (for a completely clear atmosphere). Koschmeider's law (KL) states that if the viewed object has an ideal contrast to the background, the visibility is then equal to the ratio of the natural logarithms of the viewer's contrast threshold and the transmissivity:

$$V = \frac{\ln C}{\ln T}$$

Since C and T are both less than one, the absolute magnitude of their natural logarithms becomes smaller as they become larger. Thus, a viewer is able to see farther with a lower contrast threshold, or when the transmissivity is higher.

Visibility distance and transmissivity can both be measured, but the daytime contrast threshold of the observer is a personal characteristic that varies from individual to individual. Many experimenters have tried to measure contrast threshold, both in the laboratory and the field; a compendium of their results varies by an order of magnitude --from 0.0077 to 0.073. If used in KL, these extremes would result in reported visibilities that vary by 80 percent.

The difficulty of measuring contrast threshold is a significant part of the visibility automation problem. An observer has some quality of contrast threshold, and the atmosphere has some quality of clearness (transmissivity). The observer reports the greatest distance at which he can see a specified object as the visibility. An instrument, on the other hand, measures the transmissivity and uses some chosen contrast threshold to derive the visibility. If the chosen contrast threshold is the same as the observer's, the reported visibilities will be the same; they could, however, be very different. The problem, then, is that a specific instrument-derived visibility cannot be compared to an observer's perception of visibility unless the observer's contrast threshold is known. However, the instrument-derived measurement can provide an excellent index of visibility if the user relates this index to his own contrast threshold.

The United States has adopted 0.055 as the contrast value for instrument-based computations, while the World Meteorological Organization has chosen 0.050. Used in KL, this small disparity would result in a 3-percent variation in reported visibility.

Nighttime visibility can be considered a special case of KL. However, it is simpler to apply a specialized formula, known as Allard's Law (AL), for the visual range of light:

$$E = \frac{IT^V}{V^2}$$

where E is the illuminance threshold, and I is the brightness of the light target. E plays a role in AL that is similar to the contrast threshold in KL. It is just as much as a variable as contrast threshold.

2. USERS OF VISIBILITY DATA

The users of visibility data can be grouped into three major areas: (1) atmospheric sciences, (2) land and sea transportation, and (3) aviation.

The first group requires a measure of the transmissivity of the atmosphere for forecasting and for deriving some measure of the amount of particles or aerosols in the air. The interest of this group is generally in a measurement that is representative over a large area and for time periods from 10 minutes up to an hour. The group's concern covers the entire range of visibility values.

The second group, those concered with land and sea transportation, needs a measure of visibility to assure safety. As was the case for the first group, measurements should be representative over a large area and for periods of from 10 minutes to an hour. This group, however, is not very concerned with visibility measurements above two miles.

The aviation group has two needs. A representative value much like that required by the first two groups determines whether a pilot can begin a final approach. Then, at that point, the interest of this group becomes focused on a very small and short time response. Prevailing visibility is the concept used as the large-area, long-time-frame measurement. It usually does not change appreciably from minute to minute, and it is representative of areas the size of large airports. Sector visibilities are reported to account for non-representative conditions. Runway visual range and runway visibility are used as the quick-response measures of low visibilities in the touchdown area.

Guidelines regarding minimum visibility levels are published by a number of agencies and organizations, including the Federal Aviation Administration (FAA). The FAA's Federal Aviation Regulations (FAR's) establish exit visibility values required for various aviation activities and have the effect of law.

3. TYPES OF VISIBILITY OBSERVATIONS

HUMAN OBSERVATIONS OF VISIBILITY

For human observations of visibility, there is continuing difficulty in establishing usable theoretical relationships between light, eye, target, and atmosphere that will permit visibility to be calculated quickly, accurately, and at any time. Even under the best of circumstances, a human observer encounters complex, subtle problems of a physiological, psychological, or photometric nature.

The difference between daytime and nighttime visibility concepts illustrate some of the problems facing the human observer. Each time of day imparts a different level of background luminance (that is, the brightness of the background against which a visibility marker is viewed). The act of seeing is fundamentally contingent upon the presence of a brightness contrast. Daytime visibility observations, then, are subjective evaluations of how the contrast between the target and its background has been altered by atmospheric elements such as fog, haze, rain, or snow. But at night, when the target is an unfocused, moderate-intensity light, visibility is the greatest distance a target can be perceived under given atmospheric conditions.

VISIBILITY INSTRUMENTS

The instruments that are usually described as visibility sensors do not measure visibility in the sense of detecting and identifying visibility targets; rather, they measure properties related to the physical and optical characteristics of the atmosphere. Then, through calibration and theory, the sensor measurements can be related to human observations.

Instruments in current use by the FAA and the National Weather Service (NWS) employ one of two basic techniques: the measurement of transmittance or the measurement of scattered energy. These sensors make use of one of the physical characteristics of the atmosphere--the attenuation of light by suspensoids--to determine the transparency of the air. They generally consist of an energy source, a light of some kind, and a receiver placed at a specified angle to the light to detect transmitted or scattered energy. Operational sensors used by the FAA and the NWS include the transmissometer, the Videograph, and the EG&G Forward Scatter Meter. The Fog Visiometer, the Wright and Wright Forward Scatter Meter, and the Impulsphysik FS-III are more recent developments.

AUTOMATED VISIBILITY OBSERVING TECHNIQUES

The development of visibility sensors, which can be left largely unattended and are generally capable of continuous sampling, provided a natural impetus toward completely automating the visibility observation process. One researcher commented in 1952 that the entire system of visibility targets and human estimates should be replaced by instrumental measurements of the extinction coefficients and subsequent calculation of a value of interest to the user. But researchers have long recognized that the limited sample volume sizes of sensors would necessitate time averaging and perhaps even more sophisticated data processing before automated techniques could be put into practice.

Specific objectives for automation vary. They range from determining the equivalent of prevailing visibility to developing a unique observation technique--one without a human-observed equivalent--to fulfill unusual requirements.

Runway visibility (RVV), now in generally limited use, is one of the oldest of the current generation of automated concepts. It is defined as the visibility along an identified runway, derived from transmissometer measurements from the runway touchdown zone. The algorithm for RVV is a simple conversion from transmittance to visibility. Conceptual visibility targets and reportable values of visibility are about the same as those used by human observers. Runway visual range (RVR) is an automated concept that was introduced in 1957 and is now used in virtually every country having an airport equipped with an instrument landing system. RVR is defined in the United States as a value normally determined by instruments that are alongside and about 14 feet higher than the centerline of a runway and are calibrated with reference to the sighting of high-intensity runway lights or the visual contrast of other targets--whichever yields the greater visual range.

The RVR concept is constantly under review at national and international levels. Elements under consideration include fundamental definitions, sensor height and location, reporting limits, sampling periods, and basic inputs.

AUTOB is the acronym for automatic observing station--a system that gathers and processes various types of meteorological data and, using a Videograph back scatter sensor, produces an index of visibility. The index is neither prevailing nor sector visibility; rather, it is a 10-minute average of the instrumentally-derived visibility.

The Aviation Automated Weather Observation System (AV-AWOS) is a comprehensive, multi-sensor system designed to totally automate the surface weather observation. It is the first system that attempts to provide an automated product equating directly to a human observation of prevailing visibility.

The automated visibility observing techniques described above all require the use of one or more visibility sensors. Two basic factors determine the number of sensors needed to adequately report visibility conditions: (1) the degree of resolution and representativeness required and (2) the natural variability of visibility.

4. LIMITATIONS OF VISIBILITY MEASUREMENTS

VARIABILITY OF VISIBILITY

In calibrating visibility instruments or making standard surface visibility observations, the assumption is usually made that the observer's view is representative of a relatively large area. But in fact, visibility is not often stable or uniform.

Variation of visibility is the combined effect of variations in time and space, advection past a sensor, mechanical factors, and physical characteristics of visibility-limiting phenomena. These elements cannot be separated and are thus usually measured as a single, ever-changing aspect of weather at the point of observation.

An investigation was undertaken in Tokyo to determine the extent to which measurements made at one site at an airfield are representatives of a larger area of the field. The investigator recorded changes in transmittance that were both slow and rapid, large and small, and periodic and aperiodic. In the most extreme case, transmittance changed from 0 to 87 percent within one minute.

At Newark Airport, data from a transmissometer at the end of a runway were statistically compared with data from another transmissometer near the center of the airport. The variances of simultaneously measured samples of transmittance at the two sites were not statistically equal, and differences in individual measurements were at times quite high. The researchers concluded that sensors should be located as close as possible to the region of operational importance.

Similar conclusions were reached as a result of more extensive tests at Atlantic City. The investigators recommended that at least three transmissometers be installed along a runway (at touchdown, midpoint, and roll-out) and perhaps even more at airfields with special problem areas.

Using forward scatter sensors, the Air Force conducted tests to analyze time and space variability during four classes of visibility restrictions--rain, snow, radiation fog, and advection fog. These results, too, indicated that the variability of visibility in time and space is sufficient to justify more than one automated measurement along a runway.

OBSERVER LIMITATION

Several aspects of human visibility observations are noted below, along with associated problems:

- Target. The visibility target is probably the most uncontrollable element of the visibility observation. If targets are not uniformly distributed at various distances from the observer, but instead are all within a few kilometers and are all visible, the observer will tend to overestimate visibility. Generally, a better choice of targets is available during the day than at night.

- Observation Site. Visibility observations should be taken from several locations to view as much of the horizon as practicable. However, sites with unobstructed views may not be available, and the atmospheric conditions at one site may not be representative of the entire area.

- Background Luminance. Background luminance varies between airports and observation sites. Visibility estimates derived in conditions of high background luminance would tend to be lower than those produced by the same observer with the same fog density but at a location with reduced background luminance.

- Undetected Changes. Most weather observers do not perform a continuous weather watch because they must divide their time among various weather station duties. Therefore, the making of regular visibility observations plus occasional special observations must be viewed as a discontinuous function. Changes in visibility between observations are not necessarily linear and may pass undetected by the observer.

- Dark Adaptation. This is the process by which the eye adjusts to any decrease in the prevailing brightness of its field of view. Observers who are not dark-adapted may underestimate visibility.

- Reportable Values. Of the considerable number of reportable visibility values, some are rarely used, while others are reported so frequently as to appear to be "favorites."

- Standardization of Observers. Sensitivity characteristics of the human eye vary between individuals, with time, with age, and with state of health. Therefore, selection of an individual to act as a standard observer is not scientifically practical.

As a summary note about human observations, it has been written that they provide little more than the roughest information about the optical properties of the atmosphere.

INSTRUMENT LIMITATIONS

The different methods and measurement characteristics of visibility instruments have raised questions regarding relative accuracy. In one test measuring threshold variation, noise/drift, and spatial variation, the estimated accuracy of various sensors ranged from ± 23 percent to ± 31 percent. (In the same test, accuracy estimates for human observers ranged from ± 36 percent to ± 62 percent.)

A continuing problem in the use of visibility instruments is the lack of understanding on the part of users of a sensor's capabilities and limitations. One common misconception is the belief that a sensor "sees" in a specific direction. In point of fact, the sensors noted here make only spot checks of the air moving past their zone of sensitivity, then extrapolate from the small spot samples to a much larger geographical size. A sensor's volume sample size probably has a significant bearing on accuracy, but no study has specifically addressed this issue.

Ideally, visibility sensors should be located at a site that allows measurements representative of the complete area of interest. Since few such sites exist, however, variations in visibility are a continuing source of difficulty in achieving representative instrument measurements.

Finally, outside of concurrent human observations, there is no completely adequate method for field-calibrating visibility sensors. Because the use of routine human observations for this purpose appears to contribute to the problem, dedicated observations might offer a partial solution.

AUTOMATION LIMITATIONS

Problem areas specific to RVR include the following:

- Because a pilot's eye level may vary with each approach, the accepted values for runway light intensity may not be truly representative.
- The condition of runway lights can affect RVR values.
- The RVR concept may be limited by the presence of other airport lights, including runway centerline lights.

Other problems relative to RVR that are also encountered in the use of other automation techniques are the following:

- A pilot's vision may be affected by many indeterminate factors; therefore, his visual threshold may only approximate RVR's single fixed values.
- A pilot may encounter variations in visibility that are not adequately reported, even by multiple-transmissometer systems.
- Transmissometers may not be properly calibrated.
- Pilots may not be aware of the exact nature of RVR or the fact that RVR is a probability, not an absolute value.

LACK OF STANDARDS

Although "modern" visibility research extends back through the last half-century, there is still no completely adequate method for obtaining fully satisfactory visibility observations, either human or automated.

Many studies have used observations as a standard, and routine surface visibility observations have been used in several cases to measure the performance of a sensor or system being tested. In none of these studies, however, was the standard surface visibility observation itself subjected to rigorous testing. Thus, researchers have not yet been able to gauge the true performance of a commonly accepted standard.

Other major areas of weakness in the body of visibility research include the following:

- There is no comprehensive study that documents sensor-versus-sensor tests and includes comparisons with auxiliary instrumentation (brightness sensors, telephotometers, etc.) and dedicated observers.
- So far, no study has definitively established the optimum number of sensors for coping with the largest variety of situations.

5. PERFORMANCE OF AUTOMATION TECHNIQUES

Extensive tests were conducted at Atlantic City, N.J., in 1965-1966 to validate the credibility of the RVR system. In the tests, observers counted runway lights visible to them from a height and location approximately that of a pilot at takeoff. The human observations were then compared with standard transmissometer RVR measurements. The vast majority of observers (92 percent during the day, 67 percent at night) were able to see farther than predicted by RVR. It was concluded that the disparities between the human sightings and RVR stemmed largely from the inability to standardize the human observers or users. One extremely significant finding was that no single RVR value was exactly correct for a group of observers or pilots. A possible explanation for this is that illuminance and contrast threshold values are fixed and represent a practical compromise in the RVR concept, while in actuality they vary between persons and within a single individual. In fact, perceptual variation between observers was pointed up rather dramatically by the Atlantic City tests. During several periods of time when RVR was fairly steady (between 1,600 and 2,000 feet), human counts of runway lights differed from the transmissometer by amounts ranging from -800 to +1,400 feet.

Testing of the AUTOB visibility algorithm (BV, for back scatter visibility) consisted of comparing BV to routine observations made by assigned weather observers at one site and, at another site, to observations made by dedicated test observers. Results at both sites showed good relationships between current BV and observed prevailing visibility. At one of the sites, only 12 percent of the paired observations had differences greater than one mile (although the test observers here were co-located with the Videograph, reflected the manner in which the sensor was originally calibrated).

Developmental tests of AV-AWOS used a triangular network of back scatter sensors located around the area of interest and a surface weather observer located in the center as a standard of comparison. As a result of these tests, updated AV-AWOS visibility algorithms were issued. The researchers also found that a strong relationship exists between human and Videograph measurements in the presence of hydrometeors but that Videograph measurements produce visibilities lower than those observed by humans during haze, smoke, or dust conditions. Therefore, a compromise calibration was recommended.

The AV-AWOS algorithms represent a clear breakthrough in the automation of surface weather observations. Still, several problem areas remain:

- A less subjective method than human observations must be developed for assessing the performance of automated observations.
- Since the AV-AWOS algorithms are based on a limited amount of data, further development and testing at various locations and with different instruments should be considered.
- Optimum network size and configuration have not yet been fully specified. Further testing may reveal that there are no optimum values--that, instead, tailoring to individual sites is needed. If such is the case, procedures for tailoring to individual sites is needed. If such is the case, procedures for tailoring must be developed.

6. CONCLUSIONS

As has been shown, there are fundamental differences between man-and machine-derived visibility measurements:

- The human observer provides a subjective report of visibility that is susceptible to large variations in health, light adaptation, target availability, background conditions, and viewing area. Hence, the current requirements for reporting resolution do not reflect the realities of the observer's situation.

- An instrument provides an objective report of visibility, but no adequate standards exist for assessing the accuracy, resolution, or representativeness of the report.

The observer's problems are not easily solved. Target, background, and viewing area can be expected to change, mostly for the worse, as airports become busier. The issue of standards for automation, however, can be solved. It is a complex issue, consisting of the following points:

- Sensors. We must be able to assess the accuracy and resolution of sensors and to write adequate specifications for procurement.
- Representativeness. There are several classes of users, each with conflicting needs. We must be able to standardize the number of sensors, their locations, averaging times, resolution, etc., to satisfy each requirement.
- Legal Considerations. Currently, most of the regulations that pertain to visibility are written in terms of human observations. These must be rewritten.

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1.0 SCOPE OF THE STUDY

This report has been prepared to provide a comprehensive, non-technical overview of the nature and complexities of visibility. It is intended for professional personnel who have a requirement for general familiarization with this topic.

Visibility is an element that touches us at almost every point in our lives. Low visibility can impede our driving, slow or stop aircraft traffic, and hamper shipments at sea. Bright days with high visibility can buoy our spirits and, at the same time, fill the air with general aviation aircraft.

Coping with visibility in its extremes and variations can become a life-or-death matter. Measurements and estimates of visibility conditions are essential parameters required by the National Weather Service (NWS), the Federal Aviation Administration (FAA), and other federal, military, state, and municipal groups, as well as elements of the private sector. At a minimum, we use visibility information for aircraft operations, air pollution control, environmental protection, and vehicular traffic control.

To reach the goal of this report, a large number of technical publications were assembled, each concerning a theoretical or applied research effort having visibility as its fundamental theme. First, those publications potentially suited for this type of overview were reviewed. Then, appropriate portions of relevent publications were selected and were in turn synthesized in a narrative format. The parenthetical numbers that appear in the text refer to the bibliographies found at the end of most of the report's major sections.

A strong effort was made to keep subject matter at a definitive but non-technical level. Where absolutely necessary, jargon and mathematical terms have been included in the text but receive straightforward treatment. Each technical term has been included in a glossary (Appendix A).

Publications that have made direct contributions to this report are cited in Appendix B. Where appropriate, comments have been added to the citations regarding their nature and quality. Publications on the subject of visibility that may be of general interest to the reader are listed in Appendix C, along with publications that are cited in this report but have made only a small contribution.

As an overview, this report has some rather specific limitations. Emphasis has been placed on synthesis of readily obtainable major studies; no basic research or new discoveries have been included. Because visibility as measured and used by the NWS is primarily an aviation parameter, the report is generally aviation-oriented. The history of visibility, a rather weighty subject in its own right, is treated in only the slightest of detail. Although the report respects the past, it looks mostly to the developments of the future.

2.0 OVERVIEW OF VISIBILITY OBSERVATIONS -

Many professionals who are concerned with visibility observations are often unaware of the field's numerous applications. This section discusses specifications for visibility observations and the specialty areas in which they are used. First, however, it provides a very brief introduction to the nature of visibility.

2.1 THE NATURE OF VISIBILITY

Recently, a meteorologist familiar with the vagaries of visibility stated, "Visibility, like beauty, is in the eyes of the beholder" (1)*. There is, perhaps, no better nor more concise description of the true nature of visibility.

Dr. D. Acheson of the National Weather Service states in a group of unpublished notes that there are four ingredients of visibility: target, background, atmosphere, and observer. The venerable Glossary of Meteorology (2) backs this position with the following definition of visibility: "In United States weather observing practice, the greatest distance in a given direction at which it is just possible to see and identify with the unaided eye (a) in the daytime, a prominent dark object against the sky at the horizon, and (b) at night, a known, preferably unfocused, moderate intensity light source . . . ."

The Glossary definition is virtually the same as the one published in the U.S. observing handbook, Federal Meteorological Handbook No. 1 (FMH#1) (3). This source defines visibility as "the greatest distance at which selected objects can be seen and identified." For visibility markers, it adds, "dark or nearly dark objects viewed against the horizon sky during the day, or unfocused lights of moderate intensity (about 25 cd) during the night."

A similar approach is taken by Malm (4). He writes that the process by which we see distant objects is based on the characteristics of the target, its immediate surroundings, air quality, illumination of the sight path, and, further, the eye and the brain. Malm also discusses the classical concept of visibility: visual range. He describes it as, "roughly speaking . . . the distance an observer would have to back away from a target before it disappears."

Most definitions regard visibility in practical terms, with a human observer as an element in the definition. It is possible, however, to infer visibility without the immediate presence of a human. This approach, which is receiving wide application in the automation of visibility observations, makes use of visibility instruments, including, for example, telephotometers, transmissometers, and nephelometers (2). Measurements made by most visibility meters can be kept in non-dimensional terms and can be compared without human

*See references at end of chapter.

reference. But when visibility sensors are used operationally in the field, they must be calibrated in human terms of visibility measurement.

2.2 USES AND SOURCES OF VISIBILITY DATA

Visibility plays a major but usually low-key role throughout our lives. Detection of forest fires from lookout towers is difficult or impossible during periods of low visibility. The level of transparency of the atmosphere is a vital factor for illumination and solar heating engineering. Railroad trains reduce speed during low visibility, hampering operations in switching yards. Low visibility during commuter rush hours can make a shambles of vehicular traffic flow.

Technically, visibility is not a meteorological parameter. The measure of visibility, however, is useful in general weather forecasting as a tracer and indicator of air mass characteristics. For example, a typical maritime warm air mass moving northward from the Gulf of Mexico can be recognized by several factors, one of which is low visibility. Small dust and smoke particles picked up by an air mass in its travels can be transported many miles from its original source (5, 6). However, the increasing sophistication and application of satellites may eliminate the need for surface tracers in weather map analysis.

Visibility plays a vital role in the assessment of air pollution. Changes in visibility with time can give clues to the variations of air pollution. Trijonis and Yuan (7) suggest that haze levels, usually associated with relatively small effects on visibility, may play a significant role in climate modification. In their report, based on about 25 years of airport visibility observations, Trijonis and Yuan conclude that summer is the worst season for visibility in the Northeast.

Marine requirements have historically included visibility. It has been reported that the need for systematic visibility measurements arose for the first time after the naval battle of Jutland in 1916 between the German High Seas Fleet and the British Grand Fleet. Following World War I, arbitrary scales for the visual evaluation of visibility were established (8). A more up-to-date set of marine visibility requirements was published by the World Meteorological Organization (WMO) (9). In its listing of requirements for marine meteorological services, the WMO cites several areas in which visibility information is vital; these include all classes of marine traffic, shipping, fisheries, coastal and offshore activities, recreational boating, and marine pollution. Visibility levels are specified, along with actions necessary in the presence of low visibility. Among these is the activation of lighthouse warning signals. The need to automate the signals resulted in the large-scale introduction of the Videograph to the United States by the Coast Guard. The Videograph, a back scatter sensor, is discussed along with other visibility sensors later in this report.

Since 1919, when visibility was introduced to the weather codes as an aid to aviation, it has been one of the most important aviation weather observation elements (10). Literally countless numbers of general, commercial, and military aircraft have relied on visibility observations and measurements during takeoffs and landings and enroute flight. Virtually all new developments in visibility observation technique during the last three decades have been for aviation purposes.

The reliance by aviation on visibility information is reinforced by the FAA. Its Federal Aviation Regulations (FAR's), which control aviation in the United States, have the effect of law. The FAR aviation weather operational requirements establish exact values for visibility and specify conditions during which particular aviation activities may take place. Usually, surface visibility and runway visual range are used as criteria. A considerable number of visibility observations are made by the FAA, Navy, and Air Force at least once an hour to satisfy specific aviation needs. These, along with observations made by the NWS, establish a tremendous data base of visibility information for aviation use.

A rather general approach to visibility specifications is published by the WMO in the form of a guide to meteorological instrumentation and observing practices (11). Intended for member states, some with limited resources, this guide represents a minimum specification; still, not all member nations fully adhere to it. A much more comprehensive set of specifications is published by the International Civil Aviation Organization (ICAO). Their "International Standards and Recommended Practices" (12) is frequently updated based on input from member aviation organizations. Recommendations by ICAO are usually incorporated into FAA FAR's. They are very specific and practical and are generally reflected in U.S. observing practices.

FMH#1 (3), another source of visibility specifications, is jointly issued by the U.S. Departments of Commerce (NWS), Transportation (FAA), and Defense (Air Force and Navy). It defines visibility types and describes observing technique in extraordinary detail. When FAA observations are required, annotated instructions are embedded within the FMH#1 framework. Included, for example, is the taking of tower visibility observations. NWS routine visibility observations would be taken at or near ground level. When observations are taken exclusively for aviation purposes by FAA observers, an abridged edition of FMH#1 is used.

2.3 STANDARD METHODS OF VISIBILITY OBSERVATION

Although visibility observations are specialized, they are reported in similar but not identical terms. There are many "official" observations that cannot be directly compared. For example, prevailing visibility, tower visibility, runway visibility, sector visibility, and runway visual range are all official observations; yet, if these observations were made at the same time, at the same airfield, they could not be directly compared because of underlying differences in their basic principles.

Perhaps the best way to illustrate observation differences is to define the standard methods. The following definitions have been taken largely from FMH#1 (3), with a few explanatory comments added.

Visibility. "The greatest distance at which selected objects can be seen and identified." This is a core definition on which specialized operational visibilities are based. The key word is "identified"--objects are not just seen, but are seen sufficiently well so that they can be identified. Douglas and Booker (13) report that in the past there was a movement to use the term "visual range" for the concept of visibility; as defined by the Glossary of Meteorology (2), visual range is the direct measurement made by a visibility sensor. For simplicity in this report, however, the term "visibility" is generally used, except for a particular case or two. Visibility is reported in miles in the United States (statute miles at land stations and nautical miles on naval and ocean-station vessels) according to a graduated series of increments. Increments are smallest at the lowest visibilities and increase as visibility becomes greater (see Table 1).

Prevailing Visibility. "The greatest visibility equalled or exceeded throughout at least half the horizon circle, which need not necessarily be continuous." Prevailing visibility is the fundamental parameter on which many FAR's are based. It is recorded on the official observation forms and transmitted on the various long-line weather observation teletypewriter circuits. When routinely observed from near the ground--at the NWS weather station, for example--it may be referred to as surface visibility. Under some conditions of low visibility, it is necessary for FAA control tower personnel to observe a similar parameter, tower visibility. To determine prevailing visibility, FMH#1 requires the observer to resolve individual visibilities throughout the horizon circle. This is done by using the greatest distance that can be seen throughout at least half the horizon circle. If the visibility varies during the time of observation, the observer is advised to average all observed values.

Sector Visibility. "The visibility within a specified portion of the horizon circle." When visibility is not uniform in all directions, the observer is instructed to divide the horizon circle into sectors, each of which has approximately the same visibility. The observer reports those sectors that differ from prevailing visibility and are either less than three miles or are considered operationally significant. Transmissometer data may be used to determine visibility in the sector direction of the transmissometer if the indicated visibility is less than two miles and if the observer considers the data representative. Note that sector visibility is the only case in which a visibility sensor plays a role in the surface visibility observation.

Table 1. Reportable Visibility Values

Increments of Separation (Miles)				
1/16	1/8	1/4	1	5
0	3/8	2	3	15
1/16	1/2	2 1/4	4	20
1/8	5/8	2 1/2	5	25
3/16	3/4	2 3/4	6	30
1/4	7/8	3	7	35
5/16	1		8	40
3/8	1 1/8		9	etc.
	1 1/4		10	
	1 3/8		11	
	1 1/2		12	
	1 5/8		13	
	1 3/4		14	
	1 7/8		15	
	2			

Source: Departments of Commerce, Defense, and Transportation, Federal Meteorological Handbook No. 1, 2nd ed., Washington, D.C., Jan. 1, 1979.

A visibility sensor cannot be used to derive prevailing visibility. For examples of how prevailing visibility is derived from sector visibility, see Figure 1.

<u>Variable Prevailing Visibility</u>. "A condition when the prevailing visibility rapidly increases and decreases by one or more reportable values during the period of observation."

<u>Vertical Visibility</u>. Despite its name, vertical visibility is not considered a true visibility observation by FMH#1 because it is not horizontal. The observer views the sky vertically and estimates the distance that can be seen. Vertical visibility lacks one of the major elements of horizontal visibility: the target. This definition is included here only for information.

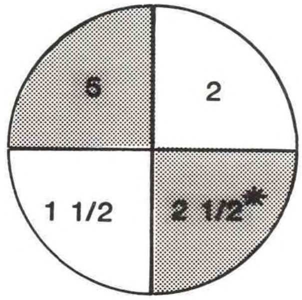
<u>Runway Visibility (RVV)</u>. "The visibility along an identified runway." RVV is reported only in special cases and rarely at a station that reports runway visual range (RVR). RVV usually uses the same photometric concepts and transmissometer measurements as RVR, but it substitutes a theoretical light of moderate intensity for RVR's high-intensity runway lights during nighttime conditions. RVV is intended to approximate non-instrumental human observations of visibility. However, it is a spot measurement and is not as representative of the overall area as the prevailing visibility concept is expected to be.

<u>Runway Visual Range (RVR)</u>. "A value normally determined by instruments alongside and about 14 feet higher than the center line of the runway and calibrated with reference to the sighting of high-intensity runway lights or the visual contrast of other targets--whichever yields the greater visual range."

EXAMPLES– Determining Prevailing Visibility
(Prevailing Visibility Indicated by Asterisks & Shading)

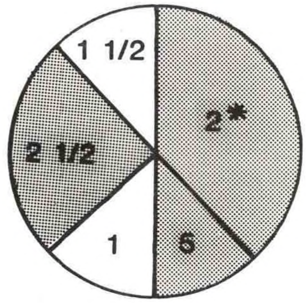
Four Sectors

Visibility (Miles)	Approximate Degrees
5	90
2 1/2 *	90
– – – – – – – – – –	180
2	90
1 1/2	90



Five Sectors

Visibility (Miles)	Approximate Degrees
5	50
2 1/2	90
2 *	130
– – – – – – – – – –	270
1 1/2	50
1	40



Six Sectors

Visibility (Miles)	Approximate Degrees
5	60
3	50
2 1/2 *	80
– – – – – – – – – –	190
2	90
1 1/2	70
1	10

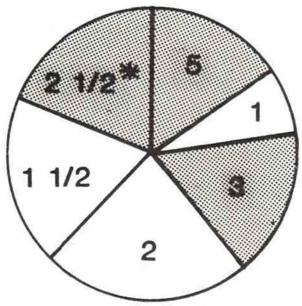


Figure 1. Determining Prevailing Visibility from Sector Visibility

Source: Departments of Commerce, Defense, and Transportation, Federal Meteorological Handbook No. 1, 2nd ed., Washington, D.C., Jan. 1, 1979, pp. A6–A12

SECTION 2

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3.0 HUMAN OBSERVATIONS OF VISIBILITY

3.1 THE OBSERVER

As outlined in Dr. Acheson's notes, the four basic ingredients of visibility are target, background, atmosphere, and observer. The first three elements occur in nature without human intervention, but an observer is required to convert a natural event into a pragmatic observation of visibility. Even in automated systems such as RVR, which routinely operates without the immediate presence of an observer, the sensor used is calibrated using a human observation of visibility. The entire RVR system, in fact, was originally derived from human observer concepts.

Human observations of visibility often represent a standard against which other methods are measured. The bible of weather observations, FMH#1 (1)*, is written in terms of the human observer. FAR's, the laws that control aviation traffic, are written from the same viewpoint.

In a sensory observation such as visibility, there is an abundance of nuances, definitions, assumptions, and theories. Middleton recognized these problems in his classic Vision Through the Atmosphere (2) when he wrote, "The problem, then, is to establish usable theoretical relationships between light, eye, target, and atmosphere that will permit the calculation of the visual range at any time; and to provide means of measuring the necessary parameters quickly and accurately enough. The problem is not yet completely solved, being a complex one." Middleton published his book in 1952, but the problem he expressed is largely still with us.

In a sense, the making of a visibility observation by a human observer seems a fairly simple process. Instructions are contained in FMH#1, and supplemental training aids are available. Designated visibility markers are plotted on charts located near the observing site. Observations are made at least once each hour, giving the observer the opportunity to increase his proficiency through practice. But even in the best of circumstances, which are rarely encountered in field operations, the observer confronts complex, subtle problems of a physiological, psychological, or photometric nature. These aspects of human observations of visibility are discussed in the subsections that follow.

3.2 DAY vs NIGHT OBSERVATIONS

Visibility observations can be made at any time of day or night. Although FMH#1 instructions and human observations tend to ignore the exact conditions, each time of day imparts a different level of background luminance--that is, the brightness of the background against which the visibility marker is viewed (3). Douglas (4)

*See references at end of chapter.

points out that such terms are used to describe visual sensations: that the brightness of a surface depends on elements of the visual image as perceived by the eye or brain.

U.S. visibility concepts are divided into day-night categories. FMH#1 does not define day or night for the human observer, but does so for RVV and RVR. In general, day continues up to that point in the evening when low-intensity lights in or near the airport complex are clearly visible. The night concept extends into the morning until those lights begin to fade. Twilight, the period that separates daylight conditions from night, is not usually recognized in U.S. civilian observations of visibility. Depending on latitude, twilight can contribute significantly to the variation of background luminance during limited portions of a 24-hour period. The moon, too, can contribute to background luminance at night, but its effect is usually never greater than, very roughly, the middle period of twilight (5, 6).

Visibility observations during daytime are subjective evaluations of how the contrast between the visibility target and its background has been altered by elements suspended in or falling through the atmosphere (e.g., fog, haze, rain, or snow). A completely different process is used at night, when the visibility target is an unfocused light of moderate intensity. Then, visibility is the greatest distance the light target can be perceived by the observer under given atmospheric conditions (1, 2, 3, 4). The two concepts are as different as night and day!

The mathematical equations that describe day and night visibility concepts are popularly known as Koschmieder's Law and Allard's Law, respectively. Although both laws were first published quite some time ago--Koschmieder's in 1924 and Allard's in 1864--they continue to serve well in the visibility field today. In addition to being the basis for general visibility concepts, they are of importance to RVR, RVV, and other automated visibility systems.

3.2.1 DAYTIME VISIBILITY CONCEPTS

Neuberger (6), writing about visibility, states, "The act of seeing is, fundamentally, contingent upon the presence of a brightness contrast." Koschmieder's Law (KL) is the basic concept of contrast used to describe visibility observations during daylight. KL relates the brightness of a target viewed against a sky or fog background to the brightness of the background and the intervening fog, haze, rain, or other atmospheric condition.

Middleton (2) is the best source of detailed information on all facets of KL. He aptly refers to the theory as the alteration of contrast by the atmosphere. He restates the nine simplifying assumptions Koschmieder made regarding his theory, some of which are neglected in practical field operations today.

There are many mathematical notations for KL, each usually representing a specialized use. Using Douglas' and Booker's (4) notation, and skipping a few of their developmental steps, we come to equations 1 and 2, which are generally referred to as Koschmieder's Law:

$$\varepsilon = e^{-\sigma V} \tag{1}$$

And since transmissivity T is equal to $e^{-\sigma}$, then

$$\varepsilon = T^V \tag{2}$$

where σ is the extinction coefficient, V is the visibility, and ε is the contrast threshold.

During daylight, black or very dark objects are ideal visibility targets. Under those conditions, equations 1 and 2 can be reduced to more operable mathematical equations:

$$V = \frac{-\ln \varepsilon}{\sigma} \tag{3}$$

and

$$V = \frac{\ln \varepsilon}{\ln T} \tag{4}$$

A direct measurement of almost all of the elements in KL can be made. Transmissivity can be measured, as can the visibility distance. But a non-dimensional ratio, describing the daytime observer's contribution to KL, represents a limit--the minimum luminance contrast at which a target is visible under stated conditions.

The numerical value of ε, the contrast threshold, is a complex and controversial matter. Neuberger (7) states that the lowest usually perceptable brightness contrast is of the order of magnitude of 0.003 under optimal conditions. But the threshold contrast is a complicated function of a great many circumstances, including the observer's probability of detection of the visibility target.

Several experiments in the past have sought to establish a representative value for the contrast threshold. Each experiment was conducted under specified and unique conditions, some under controlled laboratory conditions (8) and others under practical field conditions (9). Gordon (10) provides an extensive roundup of contrast thresholds reported by various experimenters; these range from 0.0077 to 0.073. Some of the experimenters she reports on are:

Douglas and Young	0.055
Koschmieder	0.02
Duntley	0.055
Houghton	0.06

Ultimately, the United States adopted 0.055 as the U.S. contrast threshold value, used for transmissometer-based computations of visibility. The WMO uses 0.050 (4).

It should be emphasized here that ε, the contrast threshold, does not have a direct role in the routine human observation of visibility. It is needed, however, to estimate visibility from a measurement from which an extinction coefficient can be derived or from a measurement of transmissivity.

3.2.2 NIGHTTIME VISIBILITY CONCEPTS

As described by FMH#1 (1), nighttime visibility targets are unfocused lights of moderate intensity (about 25 candelas); they may include red and green course lights of airway beacons and TV and radio tower obstruction lights. Focused lights such as airway beacons may not be used directly as markers, but their degree of brilliance can be used as a general aid. For the most part, these nighttime visibility markers can be considered point sources of light.

Middleton (2) points out that the threshold of vision for a point source of light is a special case of threshold contrast. In practice, however, it is simpler to have a specialized formula for the visual range of light. This formula can be derived from the principles of contrast discussed in the preceding subsection, but a more direct process is to apply Allard's Law (AL), which relates visibility to the illuminance produced by a distant light and the transparency of the atmosphere. In effect, AL describes the principles by which the nighttime visibility observer is governed.

Using Douglas' and Booker's (4) notation, AL can be written as:

$$E_t = \frac{Ie^{-\sigma V}}{V^2} \tag{5}$$

AL in terms of transmissivity can be expressed in the more common form:

$$E_t = \frac{IT^V}{V^2} \tag{6}$$

where E_t is the illuminance threshold, I is the brightness of the light target, σ is the extinction coefficient, T is the transmittance, and V is the visibility.

In AL, then, E_t has a role similar to ε in Koschmieder's Law. The illuminance threshold, E_t, is the minimum illuminance at the eye required to make a light source visible. The threshold is a function of the angle subtended at the eye by the source, the luminance of the background, the observer's knowledge of the location of the light, the state of dark adaptation of the observer's eye, and the criteria used in determining whether the light is visible. Usually, the threshold is not greatly affected by the color of the light (4).

The illuminance threshold is not dimensionless. Like , E_t plays an important role in the development of automated visibility observation methods.

3.3 OTHER OBSERVER ASPECTS

Several practical elements of the human observer's performance are reviewed here. A number of points have already been introduced.

3.3.1 OBSERVATION SITE

An important element is the point of observation, or observation site. With reference to the observation site, FMH#1 (1) states rather succinctly, "Take visibility observations from as many locations as necessary to view as much of the horizon as practicable." The phrase "as practicable" is required considering the hundreds of observing locations, each with unique problems for the observer (for example, an airport terminal building that obstructs half the horizon when viewed from the observation site). Since each weather station has its own horizon-limiting problems, there is virtually no uniformity of observation sites (11).

Representativeness presents another problem. Atmospheric obstructions to vision such as fog are not usually uniform over a visibility area of interest. Consider a situation in which the observation point is located in a limited zone in which the fog density equates to one-half mile. Outside this area--at other runways of an airport, for example--fog density may equate to three or more miles. The observer is not likely to be aware of a situation such as this unless notified.

3.3.2 DARK ADAPTATION

Dark adaptation is the process by which the eye adjusts to any decrease in the prevailing brightness of its field of view (3). It is a necessary preparation for any observer about to make a nighttime visibility estimate. FMH#1 advises the observer to spend as much time "as practicable" in the darkness to allow the eyes to become accustomed to the ambient illumination at the point of observation. A penalty is paid if the observer is not darkadapted: underestimates of visibility may result (11).

3.3.3 STANDARDIZATION OF OBSERVERS

FMH#1 contains basic instructions for standardizing observations, but some of these leave gaps for interpretation. The NWS, through its regional headquarters, administers an observer certification program in which observers are given a test on observing principles and sometimes undergo a limited examination of visual acuity. Further standardizing of the observer, however, seems doubtful.

Sensitivity characteristics of the human eye vary between individuals, with time, with age, and with state of health so that the selection of an individual to act as a standard observer is not scientifically practical.

3.3.4 TARGET

The visibility target is perhaps the most uncontrollable of the major elements that constitute the visibility observation and therefore may be its weakest component.

In its specifications, FMH#1 (1) employes the ideal requirement for visibility targets as outlined by Middleton (2)--that is, dark or nearly dark objects viewed against the horizon sky during the day or unfocused lights of moderate intensity (about 25 candelas) during the night. Other characteristics such as size and distribution of markers around the observing point are realistically left to circumstance. Because individual weather offices must depend on local conditions for available visibility markers, the range is great. At New York's Kennedy International Airport, for example, metropolitan buildings located at various distances from the airport and in several different directions provide a better-than-average variety of visibility markers. But at Patrick Henry International Airport in Newport News, Virginia, only a few targets are available against a tree-lined horizon. And at coastal observation sites, the flat ocean may constitute one-half or even more of the horizon.

Middleton (2) takes a rather hard look at visibility targets. He suggests having them subtend an angle of 0.5° to 1° at an observer's eye. This specification appeared in earlier editions of FMH#1 but has been omitted in the current edition. Middleton proposes that nearer markers not be too large--i.e., that a fencepost is better than a hangar when close in. He recognizes the difficulty of obtaining suitable targets uniformly distributed at various distances from the observer, but he warns that when targets are all within a few kilometers and are all visible, the observer will tend to overestimate visibility.

The observer generally has a better choice of visibility targets during the day than at night. Many objects useful as daytime targets are not illuminated at night, and lights are rarely installed for use as routine visibility markers. Those lights that are available through circumstance tend to be of various intensities and colors. A survey of available light targets at each observing station would be costly and time-consuming (2).

Several attempts have been made in the past to standardize visibility targets, but these have usually been for special test purposes (12).

3.4 PROBLEM AREAS

The problems associated with human observations of visibility are well recognized. Douglas (4) and Neuberger (7) have discussed many troublesome areas in their writings, as have Middleton (2) and Hochreiter (11). Since most problems have already been noted, only a few are reviewed here.

3.4.1 UNDETECTED CHANGES

Observations of all meteorological elements are made at least once each hour. The complete procedure takes about 10 minutes, and routine observations are completed a minute or two before the hour. In addition, special and "local" observations are taken as specific situations warrant, and observers are expected to be alert to significant weather conditions. However, NWS and FAA weather observers usually do not perform a continuous weather watch. Instead, observations must share the observer's attention with other weather station duties. As a result, the observers are not expected to detect and report all weather changes as they occur (1). Regular observations of visibility plus occasional special observations must be viewed as a discontinuous function, and changes in visibility between observations will not necessarily be linear. There may be changes, possibly even radical changes, that pass undetected by the observer.

3.4.2 HUMAN FRAILTIES

Most observers are busy people who must divide their time among a multitude of duties. There are few observers assigned exclusively to observational duties. Personal dedication to the job is traditionally good, but human frailties such as personal problems, poor morale, tension, workload, and attitude affect the quality of all work, including visibility observations. These pressures can limit dark adaptation and attention to visibility observation techniques. A heavy workload, for example, might force an observer to look out a window rather than make a possibly circuitous trip outside.

3.4.3 REPORTABLE VALUES

As previously shown in Table 1, there are a considerable number of reportable visibility values. Are all of these values used? Are there "favorite" values? Answers to these questions were provided in a recent letter to the Bulletin of the American Meteorological Society (13). Table 2 shows a frequency distribution of observations by visibility increments. Note the many "transitional" increments such as 1-1/8 and 14 miles. The record appears to show that during a 25-year period at Atlantic City, those values were not present even once during a visibility observation for the data sample.

Table 2. Frequency Distribution of Visibility Observations vs Visibility Reporting Increments

Daytime (1500 GMT, 1800 GMT, and 2100 GMT) Visibilities at Atlantic City, New Jersey (1949–73) for Observations in Which no Precipitation was Observed.

Visibility (Miles)	Frequency of Observation	Visibility (Miles)	Frequency of Observation
0	3	2 1/4	1
1/16	9	2 1/2	118
1/8	5	3	467
3/16	2	4	639
1/4	18	5	932
5/16	0	6	876
3/8	5	7	1680
1/2	17	8	1448
5/8	3	9	243
3/4	29	10	4095
1	51	11	9
1 1/8	0	12	1755
1 1/4	8	13	1
1 3/8	0	14	0
1 1/2	79	15	3503
1 5/8	0	20	2
1 3/4	3	25	3
2	114		

Source: N.M. Reiss, "Comments on Climate without 19 MPH," Letter to the Editor, Bulletin of the American Meteorological Society, Vol. 61, No. 1, Jan., 1980.

3.4.4 CONTRAST AND ILLUMINANCE THRESHOLDS

Contrast and illuminance thresholds can vary between observers and for any individual observer with time. These variations influence the results an observer achieves during a visibility observation. For example, Figure 2 illustrates 1,000 measurements of contrast threshold. Note the wide range and distribution of contrast threshold values. Middleton (2) concludes that observations provide "nothing but the roughest information about the optical properties of the atmosphere."

3.4.5 BACKGROUND LUMINANCE

Background luminance, the brightness of the background against which the visibility target is viewed at night, varies between airports and observ- ing locations. Small airports and rural locations usually have low background luminance, while large airports and metropolitan area locations have higher levels. An observer working with high back- ground luminance would tend to produce estimates of visibility that are lower than those produced by the same observer with the same fog density but at a location with reduced background luminance.

3.5 OBSERVATIONS AS A STANDARD

Routine observations of visibility should be used as test data only under these two conditions:

1. The test is fundamentally concerned with routine visibility observations, such as a blind test to determine routine observation precision.

2. The test concerns factors to be directly related to human observation, such as the performance of automated observations as compared to routine observations. In such cases, it is important that the test conductors understand the limitations of routine observations of visibility and accept or provide for them in the data analysis.

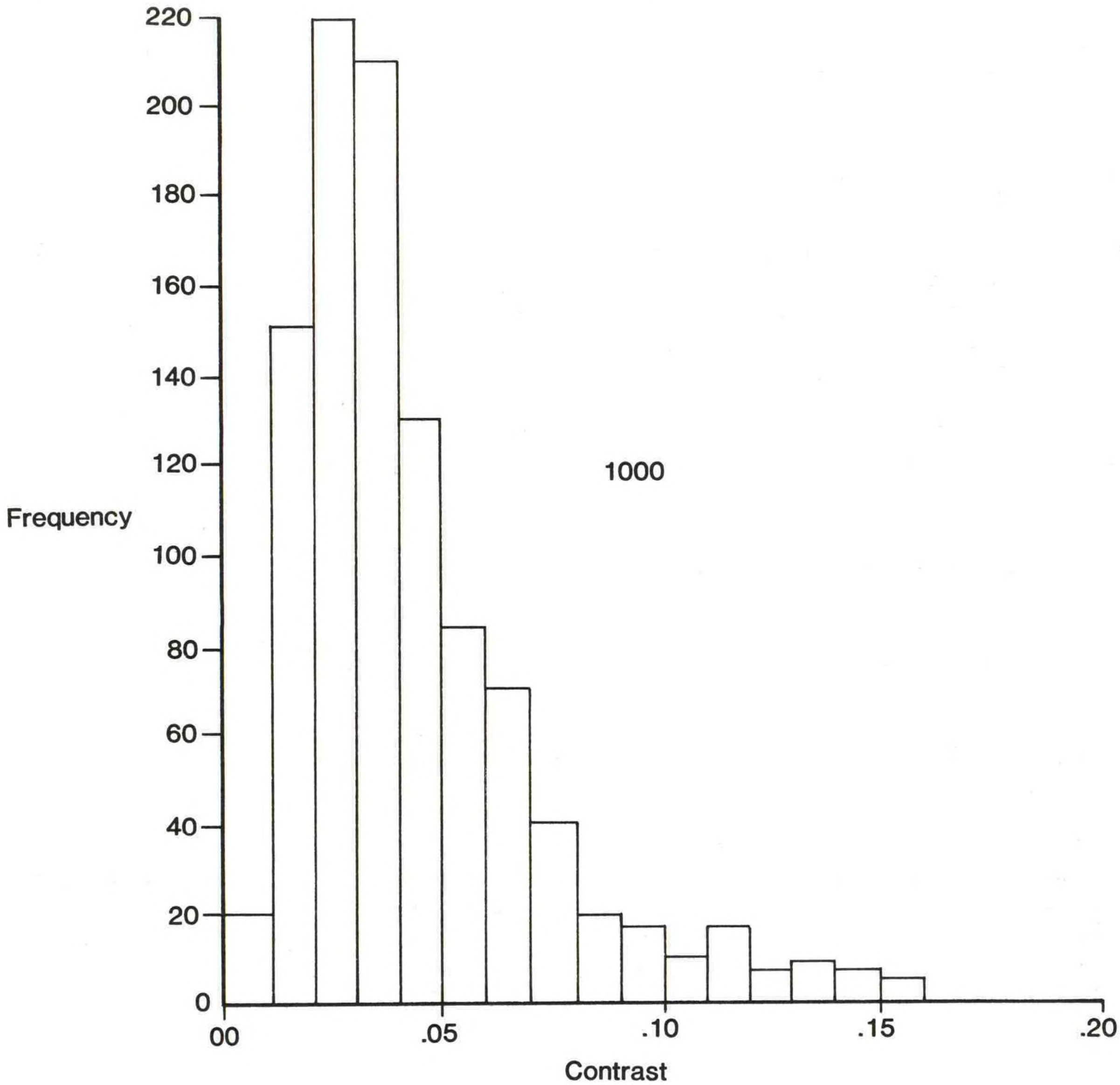

Figure 2. Frequency Distribution of Values of Contrast Threshold from 1,000 Direct Observations

Source: W.E.K. Middleton, Vision Through the Atmosphere, University of Toronto Press, Toronto, Reprinted 1963.

SECTION 3

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4.0 THE EFFECTS OF METEOROLOGICAL EVENTS ON VISIBILITY

4.1 THE NATURE OF VISIBILITY-REDUCING PHENOMENA

If Earth had no atmosphere but instead existed in a vacuum, visibility would be essentially unlimited (although there would be no observer to record that information). We do have an atmosphere, however, with both permanent and variable elements. Of the many gases that make up the atmosphere, the variable elements--water vapor, carbon dioxide, and ozone--have the most meteorological significance. The chief variable constituent, water vapor, can vary from none to as much as 4 percent of the volume of an air sample. The atmosphere also contains nongaseous variable elements, the most important of which are dust, smoke, salt particles, and condensed water. All of these affect the transmission of radiation through the air. Thus, as atmospheric components vary, so does visibility (1, 2, 3)*.

The atmospheric phenomena most likely to reduce visibility are sorted by FMH#1 (4) into two broad groups--hydrometeors and lithometeors. With respect to visibility, hydrometeors can be characterized as liquid or solid water particles that fall through or are suspended in the atmosphere or that are blown from the ground by the wind. Similarly, lithometeors are visible concentrations of mostly solid, dry particles that may also be suspended in the air or lifted from the ground by the wind. Because virtually all hydrometeors and lithometeors have an adverse but varying effect on visibility, FMH#1 carefully describes them and specifies reporting criteria and methods.

The manner in which weather affects visibility has been subjected to (and is still undergoing) many levels of theoretical research. Perhaps the strongest reason for this activity is lack of uniformity among weather phenomena. The researcher faces fluctuations in particle size and shape, water content, droplet size and shape, clarity, color, and so forth for individual weather elements and for varying combinations of lithometeors and hydrometeors occurring concurrently (5). An illustration of these problems is provided by Middleton (7). After performing a lengthy series of elaborate calculations describing visibility in fog as related to its water content, he virtually dismisses the work because actual fogs are a mixture of different droplet sizes. A knowledge of the exact distribution of droplet sizes would be needed for such calculations.

The following subsections describe the hydrometeors and lithometeors that most commonly affect visibility. There are others, but their effects on visibility are minimal or their occurrences are relatively infrequent.

*See references at end of chapter.

4.2 HYDROMETEORS AND THEIR EFFECTS

Atmospheric phenomena in the category of hydrometeors generally result from the condensation of water vapor. Condensation nuclei are required for this process. Oddly enough, these nuclei are themselves such lithometeors as sea salt, smoke, volcanic ash, automobile exhaust, and even certain bacteria and pollen (5, 7).

4.2.1 RAIN

All precipitation types are classified as hydrometeors. Rain is the fall of liquid water particles. The drops are larger than 0.02 inch in diameter, with occasional smaller drops that are widely separated. This latter state differs from drizzle, where fine drops less than 0.02 inch in diameter are very close together. Although drizzle may appear to float like fog, the drops do fall to the ground, unlike fog droplets. There are also the categories of freezing rain and freezing drizzle; however, these states have the same effect on visibility as their liquid counterparts since, during its passage downward, freezing precipitation is in liquid form.

Visibility in rain is governed by the same physical laws that govern other obstructions to visibility. Rain (and fog) droplets can affect light, and hence visibility, in various ways. Assuming a transparent and non-absorbing sphere, light can be reflected externally without penetrating the droplet, can enter the droplet and emerge with or without one or more internal reflections, and can be diffracted in passing near the droplet. Of course, these processes are complicated by the fact that raindrops are not uniform in size, are not spherical, and sometimes are not clear (6). Visibility during rain is also influenced by droplet size, the number of drops during unit time, and fall on a unit area of the earth's surface. Middleton (6) points out that visibility in a heavy thunderstorm may be much greater than during a drizzle.

4.2.2 SNOW

Snow is characterized as frozen precipitation. It consists of ice crystals, usually branched in the form of six-pointed stars. At temperatures higher than about 23° F, the crystals are generally clustered to form snowflakes. Snow may also fall as snow pellets and snow grains, which both appear as small, white, opaque grains of ice. Other less-frequently observed frozen hydrometeors that may affect visibility include ice pellets, hail, and ice prisms.

Falling snow characteristically reduces visibility, but drifting and blowing snow may continue to reduce visibility long after snowfall has ended. Sometimes the ending of snowfall may be difficult to observe due to these phenomena. Drifting snow is raised by the wind to small heights above the ground and usually (but not always) does not radically reduce visibility at eye level. Blowing snow results from more violent movement by the wind, and visibility is generally reduced to six miles or less. As snow particles are raised to greater heights, the sky may become obscured.

Snow is probably the most difficult weather phenomenon during which to observe visibility accurately. The opaque, irregularly shaped, variable-sized crystals often present a confusing visual pattern to the observer. Reflection from local light sources on the snowflakes may influence the observer's illuminance threshold and contrast threshold and could cause underestimates of visibility. Minnaert (8) reminds us of an additional optical confuser: Da Vinci's observation that snowflakes near us seem to fall faster than those some distance away. This effect might cause the observer to incorrectly report snow showers.

In a more current scientific study relating visibility to snow, Lillesaetter (9) reported that attenuation of light by snow is proportional to the rate of snowfall. Using a ratio of 18 decibels per kilometer/millimeter of water per hour, he related visibility first to attenuation and then to snowfall. Based on these factors, visibility varied inversely as the rate of snowfall, and when the rate was one millimeter of water per hour, visibility was one kilometer.

The approach taken by O'Brien (10) was to study the attenuation of light by falling snow by means of measurements of electromagnetic energy and a quantitative evaluation of type, size, and concentration of snow particles. O'Brien concluded that for a given intensity (mass flux), snow causes about 10-15 times as much attenuation of light as rainfall. This result agreed with a previous study that found that visibility was about 15 times greater in rain than in snow of the same intensity. O'Brien notes that for dry, fluffy snowflakes, the attenuation caused by a given mass flux might well be 20-25 times greater than would be caused by the same mass flux of rain.

4.2.3 FOG

Fog is defined as a visible aggregate of minute water droplets suspended in the atmosphere near the earth's surface (7). About the only significant difference between fog and clouds is that the latter are above the earth's surface.

Fog reduces both horizontal and vertical visibility. When the vertical extent of fog is greater than about 20 feet, it is reported simply as fog; when less than 20 feet, it is reported as ground fog. Ground fog reduces vertical visibility to a lesser extent than fog; at night the stars may be visible, and during daylight the sun may still be seen.

Fog is the weather element that probably has the greatest disruptive effect on aircraft operations over the largest area at the same time. The natural transition from haze makes fog pervasive and widespread.

Most of the information in the following paragraphs is synthesized from two straightforward publications: Kotsch's Weather for Mariners (11) and the government's Aviation Weather for Pilots and Flight Operations Personnel (2).

High humidity and abundant condensation nuclei are favorable factors for fog. Consequently, fogs are frequent in coastal areas where moisture is readily available. Industrial areas, where large quantities of condensation nuclei are emitted into the air, are also favorable locations for fog.

Fog is classified by the manner of formation, although formation may involve more than a single process.

Radiation fog forms as a relatively shallow layer. From a pilot's view, however, radiation fog (often called ground fog if sufficiently shallow) may conceal runway features. Conditions favorable for radiation fog include clear skies, light winds, and high relative humidities. It usually forms at night and near sunrise. Radiation at these times cools the ground, which in turn cools the air in contact with it. During calm conditions the fog may be very shallow and patchy. Light winds may cause a thicker layer, with stratus clouds forming at the top of the mixing layer. Because the cooling air drains downhill, radiation fog is thickest in the valleys; hilltops, mountaintops, and airport control towers may project above it. Shallow ground fog generally burns off after sunrise, but thicker radiation fog may persist longer or even transform to stratus clouds.

Advection fog can occur during day or night when warm, moist air moves over a colder land or water surface. It is most common along coastal areas but can develop deep in continental areas. The fog can be light, moderate, or dense with respect to visibility, depending on available moisture. As wind speed increases to about 15 knots, the advection fog layer will deepen. Stronger winds can lift the fog and transform it into cloud layers consisting of low stratus or stratocumulus clouds. From the air, advection fog appears similar to radiation fog except for the occasional cloudiness over advection fog. Also, advection fog is usually more extensive and persistent than radiation fog and can move in rapidly any time of day or night.

It should be quite apparent from the manner in which fogs and other obstructions to visibility are generated that their occurrences in time and space are extremely variable (12). Variability can be related to season, time of day, location, terrain, and basic meteorological influences. In some seasons, radiation fog may prevail, with its associated visibility characteristics; in other seasons, advection fogs may be more frequent, with quick changes in visibility. Mountain and valley areas usually produce more fogs than plains, and ocean shores and lakes have more fog days than inland areas.

4.2.4 ICE FOG

Ice fog is a condition in which many very small ice crystals are suspended in the air. As a result, horizontal visibility is reduced. When ice fog forms, temperatures are usually quite cold--below -20°F.

Arctic and subarctic cities are often subject to dense ice fog during the winter. The fog often results from the encroachment of civilization, when water vapor and the residues from combustion processes are injected into extremely cold, stagnant air. Ohtake and Huffman (13) point out that as the arctic and subarctic regions continue to develop, the effects of ice fog, including its impact on visibility, will become of increasing concern.

4.2.5 SPRAY

Spray can reduce visibility, especially when the line of sight parallels the shore. FMH#1 specifies that "blowing spray" should be reported when spray is raised in sufficient quantities to reduce visibility at eye level (6 feet on shore, 33 feet at sea) t 6 miles or less.

4.3 LITHOMETEORS AND THEIR EFFECTS

Lithometers are generally solid, dry particles suspended in the air or lifted from the ground by the wind.

Haze is usually a suspension of extremely small, dry particles that are individually invisible to the naked eye. As a numerous group, however, haze particles create a uniform veil over the landscape that appears to subdue colors. Haze can be a mixture of many types of fine particles, including salt, pollen, residue from fires, and smoke.

Smoke is a suspension in the air of particles produced by combustion. It can appear near the ground or diffused through the general atmosphere. As smoke travels a great distance, the larger particles tend to settle out. The remaining, widely scattered particles tend to transition to haze.

The term "dust" characterizes fine particles of dust or sand. These may have been suspended in the air by a duststorm or sandstorm and may have traveled great distances in air currents. As with snow, wind can blow dust or sand from the ground in large enough quantities to substantially reduce visibility.

In the atmosphere, light can be depleted and contrast altered by particulate constituents such as haze, dust, smoke, and even the 10 million tons of interplanetary debris picked up by Earth each year (14). These effects are partially due to the process of absorption--that is, the conversion of light into chemical or thermal energy. Some of the particles are hygroscopic and more readily act as condensation nuclei. Thus, these particles create a path for hydrometeors such as fog and precipitation. Haze and fog can sometimes alternate in an area, the fog burning away as the sun rises and reappearing after dark. These cycles of haze and fog can alternate until winds bring in air having fewer nuclei (14).

4.4 THE EFFECTS OF LOCAL SCATTERING

As noted above, the process of absorption affects visibility and is a significant factor in the presence of dusty or smoky air containing numerous large particles. Many particles that absorb light can also scatter light, a process that, unlike pure absorption, involves no energy retention or transformation. Scattering is a generally more important process in which small particles suspended in the air diffuse light in all directions (5, 7).

As relative humidity increases, haze or other condensation nuclei transition to fog, and profound changes occur in scattering characteristics, as evidenced by severe reduction in visibility. Fogs vary considerably in their scattering characteristics because of differing distribution of droplet sizes (14). Although absorption is negligible in a "clean" fog (15), in most cases both scattering and absorption contribute to the total extinction. Pueschel and Noll (16) report that the atmospheric scattering coefficient can be subject to strong fluctuations within relatively short periods of time, with consequent variations in visibility.

The scattering of light from sun and sky into the observer's cone of vision by particulates suspended in the air is known as airlight. Under some conditions, airlight can seriously reduce the efficiency of the visibility observer when the target is below the horizon. Consider, for example, a morning haze with high humidities. When the sun is behind the observer, visibility may be, say, six miles. When the observer turns toward the sun to estimate prevailing visibility, the airlight scatters the glare from the sun into the observer's eyes and may reduce visibility to one mile. This occurs despite the fact that the true visibility is uniform throughout the area and is not lower in any direction.

Nighttime produces a similar local effect on visibility. In this case, consider an observer who, in one direction, must view moderate-intensity light targets through an adjacent parking lot with high, bright lights. Another direction of view is across dark fields. Visibility toward the parking lot will often appear lower than visibility toward the fields.

These examples represent only two types of local scattering effects that can influence visibility observations. There are probably as many different types of effects as the number of locations where observations are made. Nothing has been found in the literature that completely documents how observers cope with the effects of scattering.

SECTION 4

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5.0 VISIBILITY INSTRUMENTS

Up to this point, visibility has been discussed in this report as a primarily subjective sensory observation. But the increasing need for objective visibility observations and the quiet, tentative emergence of automation together set the stage for the development of visibility instruments.

Middleton (1)* reports that the initial development of instruments for routine measurements of visibility occurred immediately after World War I. These early instruments were empirical and of limited accuracy and applicability. The major impetus for sensor development was the publication of Koschmieder's theories, but of the many instruments developed, few were used at weather stations. In 1941, Douglas and Young developed the transmissometer (2), paving the way for a modern generation of visibility sensors.

The instruments that are usually described as visibility sensors do not, in fact, measure visibility (3). What they do measure are properties related to the physical and optical characteristics of the atmosphere, as opposed to the distance at which an observer can detect and identify a visibility target. Through calibration and theory, the sensor measurements can then be related to human observations.

5.1 VISIBILITY SENSOR TYPES

Visibility instruments in current use by the FAA and the NWS employ one of two basic techniques: the measurement of transmittance or scattering. These sensors use the physical characteristics of the atmosphere--attenuation of light by suspensoids--to determine the transparency of the air. The sensors generally provide an energy source, a light of some kind, and a receiver at a specified angle to the light to detect scattered or transmitted energy.

In the United States, the most common method of determining visibility by use of a sensor is the measurement of transmittance (4). A version of the National Bureau of Standards transmissometer is used for this purpose. In this concept, a projector with controlled output beams across a known path to a photometer (receiver), as illustrated in Figure 3. The light energy is attenuated by atmospheric suspensoids in the receiver's field of view. The light at the receiver in perfectly clear air (no losses) is considered to be 100 percent, and the percentage of light received during periods of lower visibility is the transmittance. This value can be converted to visibility and RVR using the appropriate equations.

Scattering sensors are a bit more complex. Those in use today in the United States generally fall into two categories--forward

*See references at end of chapter.

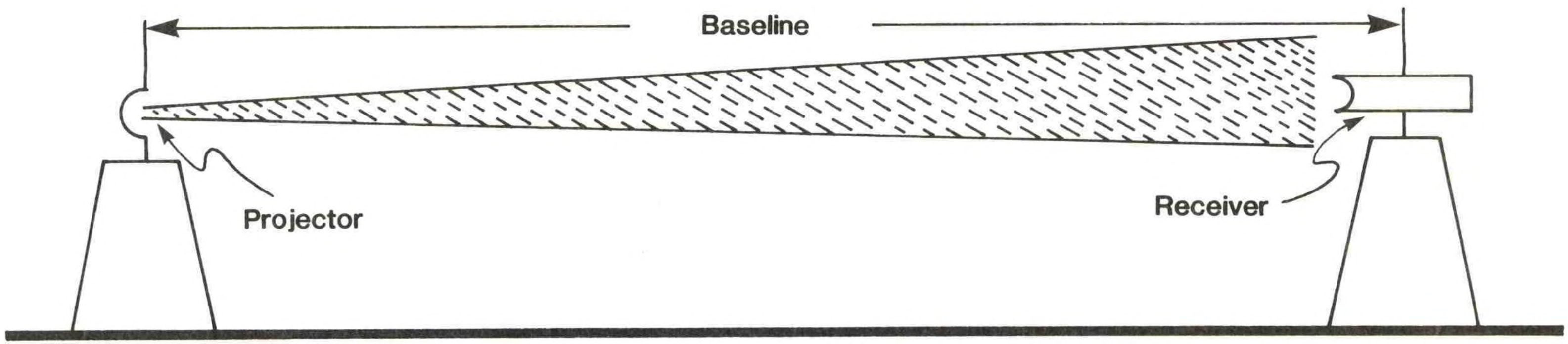

Figure 3. Transmissometer Measurement Method

SOURCE: F.C. Hochreiter, Analysis of Visibility Observation Methods, Environmental Science Services Administration, Technical Memorandum WBTM T & EL 9, Sterling, Va., Oct., 1969.

scatter sensors and back scatter sensors. Figure 4 schematically illustrates the fundamental differences between the two types. The "incident beam" shows the direction in which the sensor's projector is oriented. The receiver's orientation along the "scattered ray" line determines whether the sensor detects forward scatter, back scatter, or even total scatter. Figures 5 and 6 graphically illustrate the principles by which forward scatter and back scatter sensors operate.

Hochreiter (4) summarizes the characteristics of each measuring principle as follows:

1. Transmittance Types

   a. Many years of proven and accepted service.
   b. Measurement path is longer than most other visibility measuring systems.
   c. Measurement considers both light scattered and light absorbed.
   d. The use of multiple baselines permits measurements for all ranges of visibility.
   e. Although measurement path is longer than most other visibility measuring systems, its indication still may not be representative of surrounding conditions.
   f. Accuracy varies with baseline length.

2. Back Scatter Types

   a. Compact design.
   b. Simple one-point installation.
   c. Accuracy constant.
   d. Assumes no absorption of light, an assumption not always correct.
   e. Dependent on particle size and distribution.

3. Forward Scatter Types

   a. Relatively insensitive to particle size.
   b. Compact design.
   c. Simple one-point installation.
   d. Short measuring path.
   e. Assumes no absorption of light, an assumption not always correct.
   f. Accuracy constant.

Several other types of sensors not in current use in the United States deserve mention. Among them are such popular instruments as telephotometers and nephelometers.

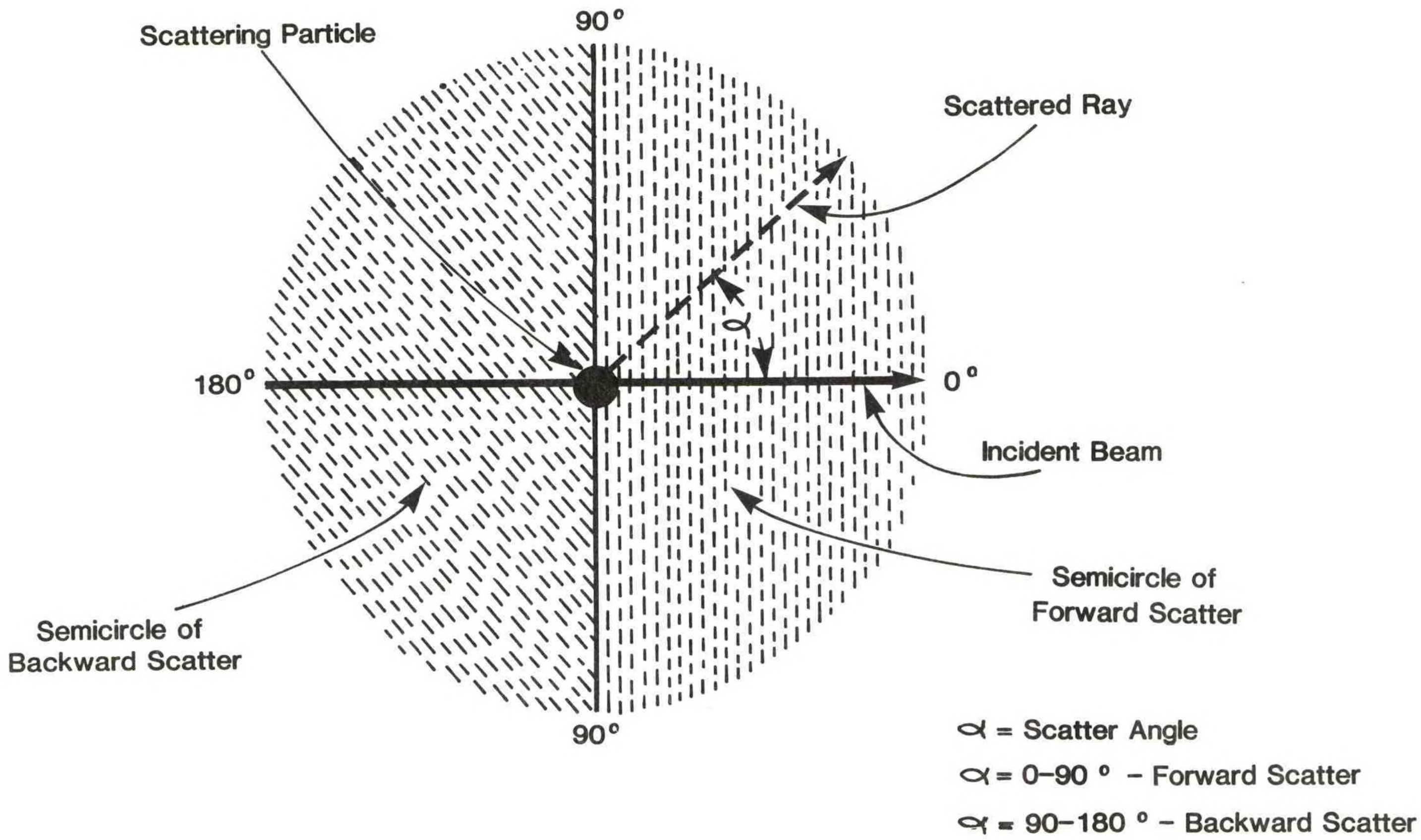

Figure 4. Relationship Between Scatter Angle and Type of Scatter

Source: F.C. Hochreiter, Analysis of Visibility Observation Methods, Environmental Science Services Administration, Technical Memorandum WBTM T & EL 9, Sterling, Va., Oct., 1969.

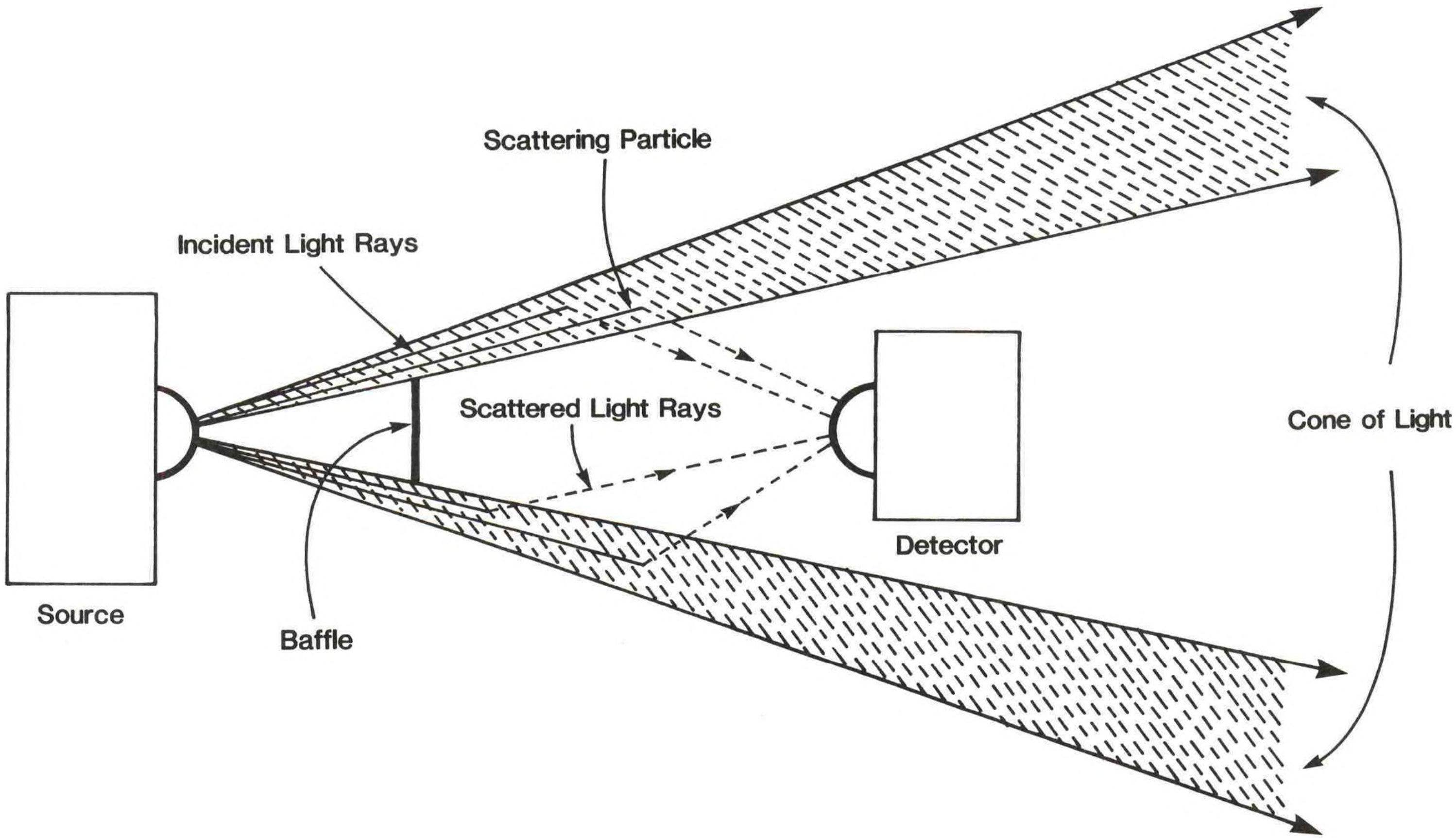

Figure 5. Principles of Forward Scatter Visibility Measuring Systems

Source: F.C. Hochreiter, Analysis of Visibility Observation Methods, Environmental Science Services Administration, Technical Memorandum WBTM T & EL 9, Sterling, Va., Oct., 1969.

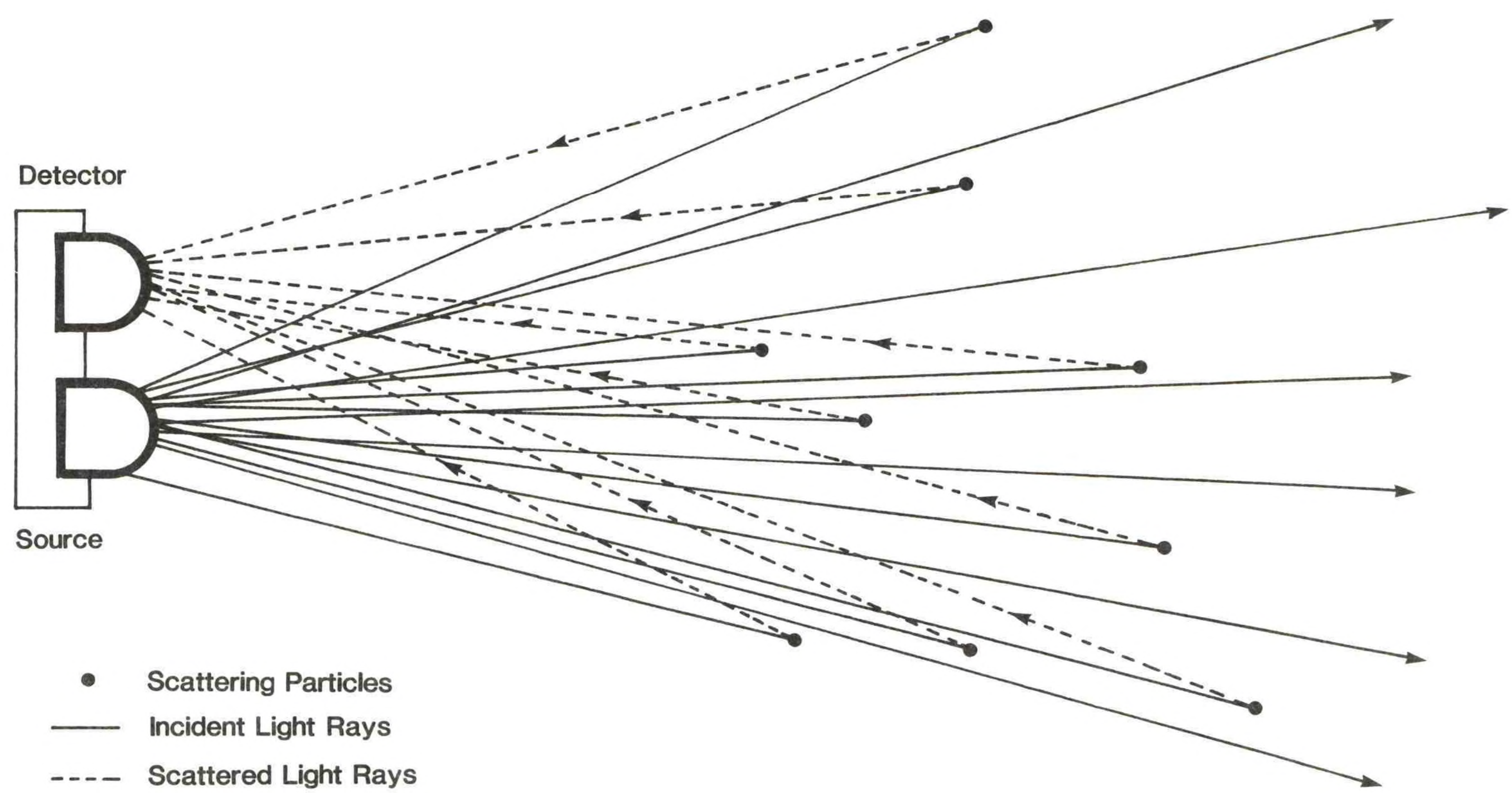

Figure 6. Principles of Back Scatter Visibility Measuring Systems

Source: F.C. Hochreiter, Analysis of Visibility Observation Methods, Environmental Science Services Administration, Technical Memorandum WBTM T & EL 9, Sterling, Va., Oct., 1969.

One type of telephotometer compares the illuninance from a distant light source with that from a comparison source in the instrument. Another type measures the relative brightnesses of two distant targets (5)--for example, a dark building and the horizon above it.The type that compares light sources can best be used during nighttime, the other during the day. For purposes of this report, both types will be known simply as telephotometers.

The scattering coefficient can be directly measured by an integrating nephelometer. This instrument is based on the principle that when a simple aerosol volume is illuminated by parallel light, light will be scattered from the illuminating beam in all directions.

Several recent tests have utilized telephotometers and nephelometers (5, 6). Cwalinski _et al_. (5) reported that the telephotometer derived visibilities correlated significantly (r = 0.83) with local human visibility estimates at the lower visibilities (0-5 miles). The authors found that results for the nephelometer were significantly less favorable than those for the telephotometer, and a transmissometer used as part of the test array performed even less well. Note that the transmissometer was not the National Bureau of Standards type, but a laser transmissometer. The authors recorded several problems associated with the laser transmissometer (a folded-baseline type), including the need to manually position the transceiver mount to get maximum return from a retroreflector.

5.2 OPERATIONAL VISIBILITY SENSORS USED BY THE FAA AND NWS

5.2.1 THE TRANSMISSOMETER

The visibility sensor in greatest aviation use today is the transmissometer, an extinction-type instrument. It serves primarily as the national RVR sensor. The history of the transmissometer is lengthy, and the sensor has been the subject of considerable modification and updating, but it still remains in principle as originally developed by Douglas and Young in 1941 (2).

The transmissometer sensor consists of a projector and a receiver atop 14-foot towers (see Figures 3 and 7). The baseline, which varied somewhat through earlier years, is now usually set at 250 feet and 500 feet. Because of the non-linear relationship between sensor measurements and visibility, the shorter baseline is best used for lowest RVR's and the larger baseline is more appropriate for higher visibilities. These differences are a practical result of the transmissometer's characteristics. The light source is unmodulated, operating at a fixed intensity. The receiver outputs pulses with a frequency proportional to the illuminance on the receiver.

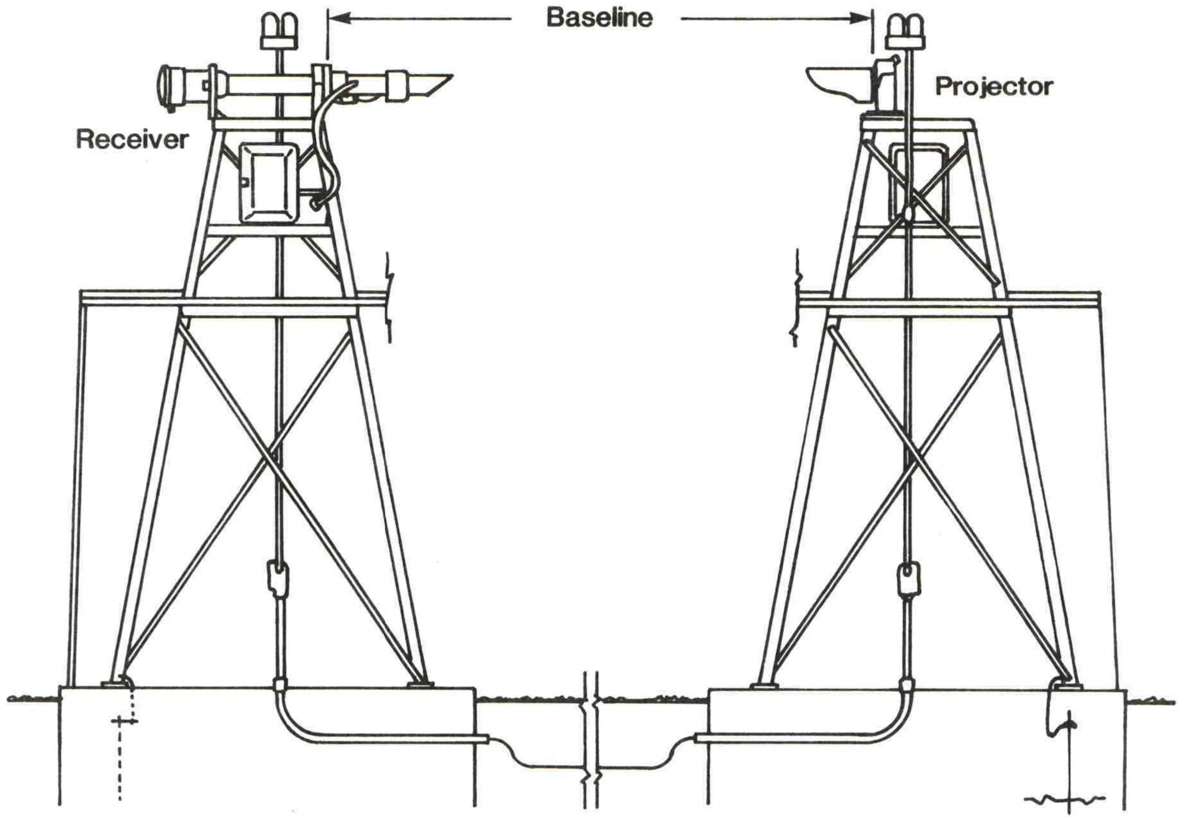

Figure 7. The Transmissometer System

Source: C.A. Douglas and R.L. Booker , Visual Range: Concepts, Instrumental Determination, and Aviation Applications, National Bureau of Standards Monograph 159, Washington, D.C., June, 1977.

There is also an amplifier and an indicator that includes a counting rate meter. These elements, along with an analog recorder, provide calibration monitoring and control functions.

A field calibration of the transmissometer was undertaken by the Weather Bureau in 1952 at Washington National Airport, Washington, D.C. An observer reported visibility near the end of the runway. His readings were compared with measurements made by a transmissometer nearby but not coincident. Visibility targets were ordinary buildings, trees, lights, etc. Special visibility targets were not used, and the number of test observations was relatively small.

In their test report (7), the Weather Bureau accepted Douglas' daylight calibration of the transmissometer (equation 2). Although their data indicated a slightly lower contrast threshold than Douglas had determined, his value of 0.055 was "tentatively accepted for visibilities of three miles or less in fog."

Although Allard's Law is the generally accepted convention relating illumination from a point source through an aerosol, Douglas found another expression that better described transmissometer calibration at night (2):

$$S_0 = \frac{IT^D}{D} \tag{7}$$

where S is the observer's illuminance threshold empirically set at 0.084 candelas per mile, I is a nominal 25-candela light target, T is transmissivity, and D is distance from observer to visibility target. Equation 7 is used only for nighttime RVV.

A twilight calibration was also developed by Douglas and Young. Except for some early testing, it has never been used operationally by the NWS or the FAA.

Acceptance of the transmissometer has continued for many years despite its evident problems. Today it is considered a standard against which other visibility sensors are compared.

5.2.2 THE VIDEOGRAPH

The visibility sensor in second greatest use in the United States is the Videograph, a back scatter-type instrument designed by Frank Frungel of Impulsphysik GmbH, Hamburg, Germany. Systems in use have also been manufactured in the United States.

The Videograph (Figure 8) is a single-ended sensor consisting of a unitized projector and receiver mounted on a sturdy pedestal. The projector is tilted upward about 3.5° with respect to the receiver's field of view. The axes of the projector and the receiver intersect about 17 feet from the sensor. The light source for the Videograph

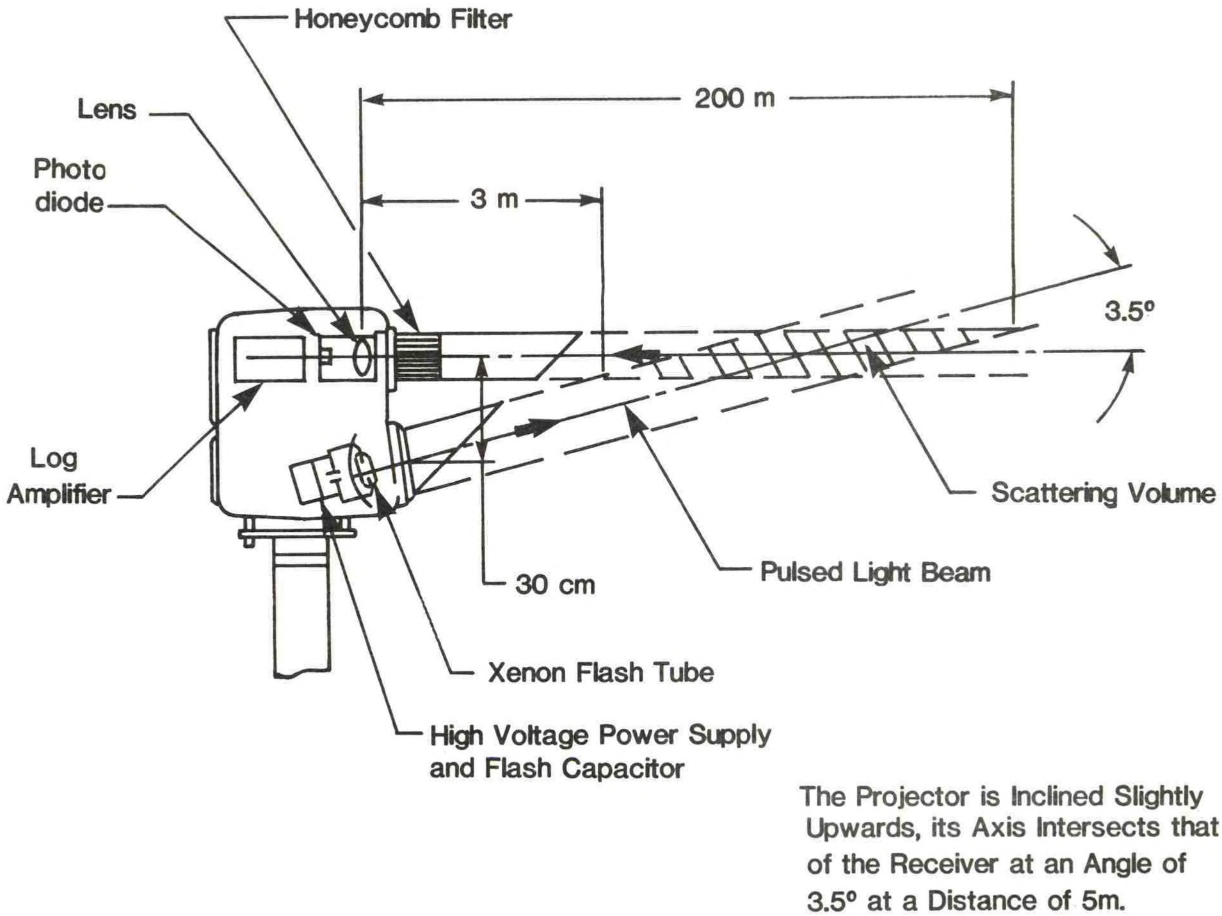

Figure 8. Diagram of the Videograph

Source: B.E. Sheppard, Calibration of Scattering Function Visibility Sensors at Toronto International Airport March 1973 to December 1975, Canada Atmospheric Environment Service Report TR 4, Toronto, Dec., 1978.

is a specially selected xenon lamp that flashes each 1.2 to 1.5 seconds, with a flash duration of about a microsecond. The intensity of the back-scattered light is a measure of visibility.

The Coast Guard initially introduced the Videograph to the United States as a fog detector for unmanned aids to navigation (8). Their interest in the sensor was primarily for detection of offshore fog banks, with visibilities in excess of three miles.

The NWS analyzed the performance of the Videograph in 1971 (9). After a year of experience with the sensor, investigators found a good relationship between the transmissometer and the back scatter sensor. Impressed with the easy field application, no-failure reliability, easy maintenance, and calibration stability, the investigators recommended further evaluation.

Following the promising results of the earlier investigation, the NWS went on to calibrate the Videograph (10). Data were taken and were compared with human observations at Washington National Airport; Dulles International Airport, Chantilly, Virginia; Elkins, West Virginia; Allentown, Pennsylvania; and Fairbanks, Alaska. Data at the latter station were not used because of questions regarding the performance of the Videograph in ice fog and adequate visibility markers for test purposes.

The results of these tests showed that different calibrations might be appropriate, depending on the nature of the occurring weather. Since sensors indicating type of weather had not yet been developed, the investigators recommended that the operational calibration be based on composite data for fog/haze and day/night. The NWS later needed a single calibration for combined day/night data, and a single compromise curve was furnished to be used at AUTOB-Type stations (11).

Vogt (12) conducted tests of the Videograph in Berlin in 1967. He, too, compared the Videograph with human observers. His conclusions were that back scatter sensors indicate visibility about as well as other types of sensors, with an accuracy of about ± 20 percent if no completely abnormal distribution of aerosol particles is present. Vogt stated that back scatter sensors should be calibrated by parallel measurements with transmissometers and, further, that calibrations should be localized depending on the nature of suspended particles. He also detected differences in Videograph performance depending on the type of obstruction to vision. He found that the Videograph indicates visibilities lower than those observed in snowfall and some fogs. This finding somewhat parallels the NWS study (9), which showed visibility readings lower than those observed in snow and, to some extent, in rain.

The Canada Atmospheric Environment Service has long had a strong interest in the Videograph (13, 14, 15). They compared the Videograph with human observers and visually fit curves to plots of the data. They confirmed an inverse linear relationship between the Videograph output and the logarithm of prevailing visibility for all conditions except for fog below one mile and above six miles. They found that as visibilities decreased, the Videograph progressively underindicated visibility in snow and overindicated visibility in rain. The reference value was to visibility in fog.

5.2.3 THE EG&G FORWARD SCATTER METER

Another visibility sensor that has received attention in recent years is the EG&G forward scatter unit (16). The EG&G Forward Scatter Meter is built as a single unit consisting of controls and electronics and two support arms holding projector and receiver assemblies. The light source is a quartz halogen lamp configured to project a cone-shaped light beam over the range of 20° to 50° from the center axis toward the receiver (Figure 9). Light impinging on the detector from scattering caused by particulates or aerosols in the sampling volume is linearly related to the atmospheric extinction coefficient. The manufacturer rates the system as useful for 20 to 20,000 feet.

The Air Force Cambridge Research Laboratories (AFCRL) have had a great interest in the forward scatter sensor, as they were largely responsible for developing and modifying the sensor. AFCRL deployed 30 such instruments in Massachusetts in a network of automatic weather stations. They reported that comparisons between forward scatter sensors and transmissometers yielded differences of ±19 percent (17). Comparisons with human observations of visibility showed differences of ±34 percent and greater. The investigators encountered some problems with human observations and were forced to separate Air Weather Service human observations from those of FAA observers, partially as a result of large differences between the two sets.

After more than 100 instrument-years of experience with the forward scatter sensor, AFCRL concluded that it provides reliable, accurate, and representative measurements of the atmospheric extinction coefficient at a point location "in all kinds of restrictions" (18). Comparisons made between human observations and transmissometers on 250-foot and 500-foot baselines supported AFCRL's arguments that point measurements are highly correlated to a line or area measurement except in highly variable conditions such as patchy ground fog.

Correlation coefficients between the Videograph and forward scatter meter were found to be very high in almost all weather conditions except snow. AFCRL credited this result to enhancement of the backscattered signal off snowflakes, which concurred with previous findings by the NWS, the Canadians, and Vogt.

As a parallel to AFCRL's interest in the forward scatter meter, the Canadians have recommended that the sensor, with some modifications, be considered the prime candidate for future automated applications.

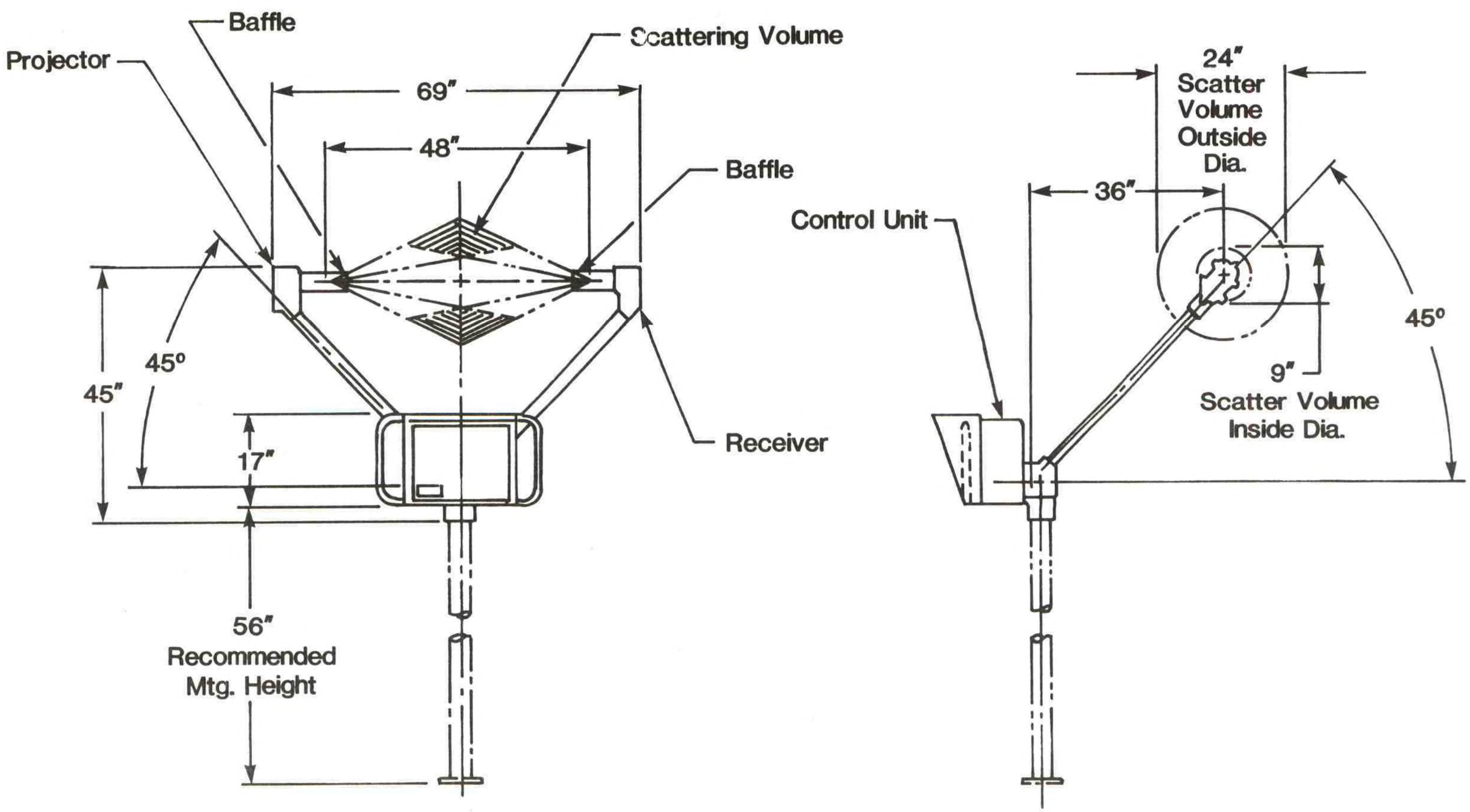

Figure 9. Diagram of the EG & G Forward Scatter Meter

Source: B.E. Sheppard, Calibration of Scattering Function Visibility Sensors at Toronto International Airport March 1973 to December 1975, Canada Atmospheric Environment Service Report TR 4, Toronto, Dec., 1978.

5.2.4 OTHER VISIBILITY SENSORS

Several other visibility sensors have appeared on the market but have not yet been as fully tested as the transmissometer, the Videograph, and the EG&G Forward Scatter Meter. One relatively new sensor is the Fog Visiometer, manufactured by Meteorology Research, Inc. Like the forward scatter meter and the Videograph, it consists of a centralized housing from which both a projector and receiver emerge (Figure 10). The projector, a xenon flashlamp, illuminates a relatively small sampling volume through an opal diffusion filter. The detector, a photomultiplier tube, looks into a light trap at the opposite end of the sensor. The output voltage of the instrument is linearly proportional to the scattering coefficient. The sensor integrates scattered light from 7° to 170° and is sometimes known as a "total scatter" type.

AFCRL test results (18) show that the Fog Visiometer has consistent calibration with the Videograph and the forward scatter meter during fog and rain. However, the Visiometer can be erratic in light rain and performs poorly in snow. The Canadians also tested the Fog Visiometer (16), but the results were limited due to instrument problems. They did find larger standard errors for snow conditions, which they believed were caused by the small sampling volume. This effect did not occur to the same degree in fog.

An instrument that has not yet received much attention in the literature is the Impulsphysik FS-III Visibility Meter (formerly Fumosens), a forward scatter sensor. The manufacturer claims several visibility ranges depending on calibration.

5.3 PROBLEM AREAS

In the informative AFCRL report on the forward scatter visibility sensor (17), the authors state that "it is clear that a new era of visibility measurement has begun." Although this statement is true, there seems to be no sensor available today that can be fully accepted for automation of aviation visibility observations without either qualification testing or further modification.

5.3.1 USERS' EXPECTATIONS AND UNDERSTANDINGS

One persistent but understated problem is the lack of a comprehensive understanding by the user of a sensor's capabilities and limitations. Unfulfilled expectations often lead to disappointment and to an overall but unfair dismissal of a sensor's worth.

One myth that occasionally surfaces is the belief that a visibility sensor "sees" in a specific direction. This may be perpetuated by the directional appearance of the Videograph and perhaps by the definition of RVR--specifically, the "along the runway" statement. The visibility sensors discussed in this report make only spot

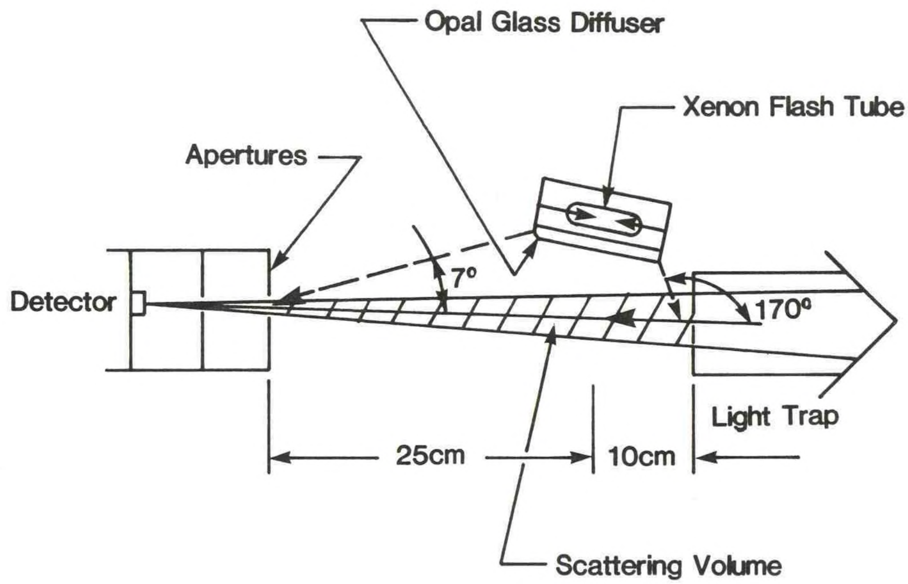

Figure 10. Diagram of the MRI Fog Visiometer

Source: B.E. Sheppard, Calibration of Scattering Function Visibility Sensors at Toronto International Airport March 1973 to December 1975, Canada Atmospheric Environment Service Report TR 4, Toronto, Dec., 1978.

checks of the air moving past the sensor's zone of sensitivity--a relatively small volume sample. Sensitivity varies with the distance between projector and detector, with wind speed and direction, and sometimes with weather type. The small spot samples are then extrapolated to a much larger geographical size (visibility distance, or area visibility), a step that assumes uniformity of visibility throughout the area. But never does a visibility sensor "see" in a direction.

5.3.2 MEASUREMENT ACCURACIES

The instruments discussed in this report have different measurement characteristics and methods (extinction, forward scatter, back scatter, and total scatter). These differences have raised questions regarding relative accuracy. But when considering weather phenomena, even the term "accuracy" has not been conclusively defined. AFCRL conducted a survey of published literature over a 30-year period ending in 1974 (17). They found that few experiments had been conducted on the accuracy of reported visibility. AFCRL further uncovered the embarrassing fact that more than 10,000 visibility observations are taken by weather services every day, archived, and used in forecast research--all without quantitative accuracy statements. The AFCRL did make some accuracy estimates of their own; because of their importance, they are reproduced verbatim in Table 3, along with their extensive notes.

5.3.3 VOLUME SAMPLE SIZE

A visibility sensor's volume sample size is probably a significant factor, but evidently no study has been conducted to specifically establish this as fact. Sheppard (16) implies that the small sampling volume of the MRI Fog Visiometer is responsible for that instrument's measuring error. No figures are given, but its volume sample seems to be the smallest of any sensor discussed in this report. Impulsphysik does not note volume sample size in their specifications for the FS-III Visibility Meter, but it seems somewhat larger than the Fog Visiometer's. Next in increasing size is the Model 207 Forward Scatter Meter; EG&G specifies the sampling zone as a toroidol-shaped space about 2 feet in diameter with a total volume of 1.67 cubic feet. The sampling volume of the Videograph has been estimated as about 13 cubic feet extending immediately in front of the receiver/projector (16). No published figures have been found on the volume sample size of the transmissometer. However, considering a baseline of 250 or 500 feet, its sample may be the largest of the sensors reviewed in this report.

5.3.4 FIELD CALIBRATION

Field calibration of visibility sensors is a problem under continuing investigation but with no perfect solution in sight. Human observation of visibility, always a rather uncertain quantity, is often the standard against which sensor measurements are compared.

Table 3. Estimated Errors in Determining the Visibility along the Runway with Different Observing Systems

System	Range	Threshold Variations [b] (%)	Noise, Drift (%)	Spatial Variations (%)		Net (%)
4 FSM(1 per km) [a] (1-Minute Avg.)	0–5 km	± 15	± 4	± 15		± 23
Transmissometer 1, 152m Path	0–1.8 km	± 15	± 15 [c]	± 35		± 40
Transmissometers 2, 152m Path	0–1.8 km	± 15	± 11	± 25		± 31
		Threshold Variations (%)	Systems Prob. [d] (%)	Time Lag (%)	Spat. Var. (%)	Net (%)
Prime Duty Observer, Day	0–5 km	± 25	± 15	± 20	± 10	± 36
Prime Duty Observer, Night	0–5 km	± 25	± 25	± 30	± 20	± 50
Secondary Duty Observer, Day	0–5 km	± 25	± 25	± 30	± 10	± 47
Secondary Duty Observer, Night	0–5 km	± 25	± 35	± 40	± 20	± 62

SOURCE: H.S. Muench, E.Y. Moroz, and L.P. Jacobs, Development and Calibration of the Forward Scatter Meter, Air Force Cambridge Research Laboratories Report No. AFCRL-TR-74-0145, Instrumentation Paper No. 217, Bedford, Mass., Mar., 1974.

The transmissometer is field-calibrated through comparison with on-site human visibility observations on days with high, uniform visibility (five miles or more), after elaborate mechanical and electronic alignment (2). High visibility tends to reduce human estimation errors based on transmissometer vs. visibility relationships. However, the high visibility requirements for transmissometer calibration can cause problems. If, for example, a projector lamp failed during low visibility conditions, the entire system, including RVR, would be out of service until high, uniform visibility was again present. In order to calibrate the system during lower visibilities, a new procedure had to be developed (19, 20, 21). A laser system was evaluated in an effort to reduce reliance on human observations (22).

The Vivical, a Videograph calibrator, seems to elicit mixed feelings about its utility. Recently, the Canadians developed a device similar to the Vivical that they believe is satisfactory. Units are being tested by the NWS's Test and Evaluation Division. In practice, NWS Videographs used in the field are routinely shipped to the Sterling R & D center in Virginia for comparison with a master Videograph. Differences, within specified limitations, are adjusted out of the field sensor. The master unit is kept in calibration by comparison with a series of human observations taken during low visibilities.

The EG&G Forward Scatter Meter uses both a laboratory calibrator and a field calibrator (17). The laboratory calibrator is a large, translucent screen mounted between the projector and the detector. Users are concerned that the laboratory calibrator, which is too bulky for routine field use, might be altered by environmental factors and thus might affect calibration of the sensors. The field calibrator is a tube that extends from projector to detector, but light leakage seems to be a problem.

No completely adequate method of field-calibrating visibility sensors appears to exist outside of concurrent human observations of visibility. Since the use of routine human observations of visibility for calibration was found to contribute to problems (17), dedicated observations might be a partial solution.

5.3.5 SENSOR SITING AND REPRESENTATIVENESS

The ideal site for a visibility sensor would be one that provides measurements representative of the complete area of interest. However, there are few, if any, such sites. Another way to achieve representativeness would be to install an unlimited number of sensors--but there are few, if any, such budgets.

Variations in visibility are a major cause of the difficulty encountered in achieving representative instrument measurements of visibility. Some large-scale differences can be filtered out by proper processing of the raw data, as opposed to reliance on minute-to-minute measurements. But local problems can be more difficult to overcome. For example, a visibility sensor might be sited in an aircraft run-up area, as was done in New York City several years ago. When the wind direction is right, aircraft exhaust can affect sensor readings. Visibility sensors have been installed downwind of smoke plumes, adjacent to air conditioner effluent, and near truck roadways. Such problems may not be obvious at the time sensors are sited and installed.

How high up should visibility sensors be installed? The Videograph is installed about 5 feet above the ground, and the transmissometer is about 14 feet above the runway centerline. Some choice exists with the other sensors.

Another factor is the required visibility resolution. When the FAA specified fine resolution for RVR, it was found that at least three transmissometers would be needed along a runway to satisfy the requirements (23).

Siting of visibility sensors should receive as much attention as, say, a new airfield runway. Local effluent sources must be considered, as well as terrain and climatology.

SECTION 5

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6.0 AUTOMATED VISIBILITY OBSERVING TECHNIQUES

The previous section discussed the development and use of several different visibility sensors and touched on the progression toward "the coming era of automation" (1)*. The sensors, largely unattended and generally capable of continuous sampling, provided impetus toward automation of visibility observations by offering the opportunity to maintain or increase weather observation services while keeping within staffing limits. Automation even held the possibility of more significant work for personnel, since automated observing systems provide a virtually continuous weather watch while requiring only minimal human intervention--by an observer for calibration and a technician for maintenance.

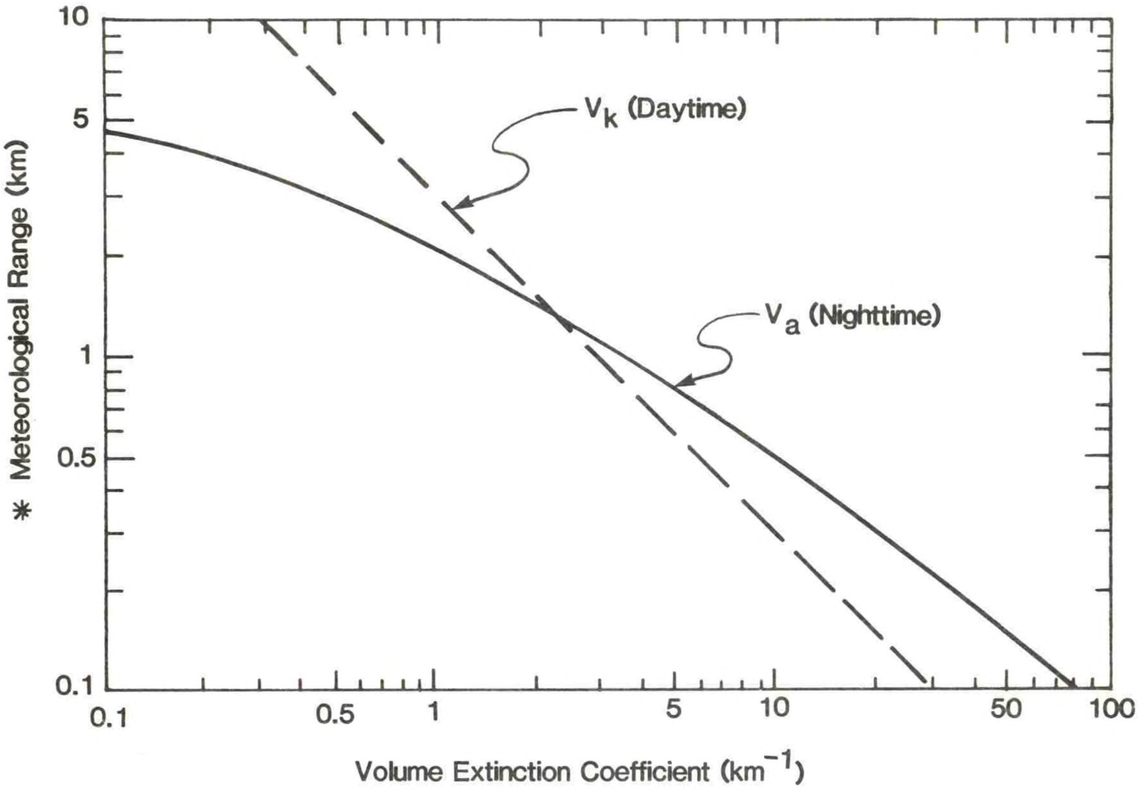
6.1 PROCESSING OF SENSOR DATA FOR AUTOMATION

Researchers have long recognized that, due to the limited sample volume sizes of visibility sensors, time averaging and perhaps even more sophisticated processing of data would be required for the development of automated visibility observing techniques. "How often should one measure?" Jiusto asked (2). His answer was that, obviously, frequency of measurement depends on specific objectives and time fluctuations of, in this instance, fog variables.

Specific objectives for automation vary. In some cases there is a need to determine the equivalent of prevailing visibility. In others, the objective is to develop a unique observation technique to fulfill unusual requirements. The result could be a visibility observation that would not have a human-observed equivalent.

What data should be processed in an automated visibility observing system? Obviously, using the direct measurements made by the visibility sensor would be convenient and would reduce computer requirements by eliminating conversion steps or look-up tables. But the relationship between sensor measurements and visibility (through such intermediate steps as Allard's Law and Koschmeider's Law) may not be of a simple, linear nature. For example, in their investigation of strategies for the automation of prevailing visibility, Mancuso and Uthe (3) considered the extinction coefficient to be the basic parameter of their visibility model. But they point out that the transformation of the extinction coefficient to day/night visibility could lead to some disparities. They illustrate this problem in Figure 11, which depicts visibility as a function of the extinction coefficient. If a simple average of the extinction coefficient were used to represent visibility, it would be necessary to compensate for the non-linear relationship; the simple average alone would not be adequate.

*See references at end of chapter.



* Assumptions:

- Day Contrast Threshold 0.055
- Night Visual Illuminance Threshold

  2 Mile-Candles And Source Intensity Of 25 Candela.

Figure 11. Meteorological Range as a Function of the Volume Extinction Coefficient

Source: R.L. Mancuso and E.E. Uthe, Computer Model for Investigating the Strategy of Automatically Estimating Prevailing Visibility, Stanford Research Institute, Menlo Park, Calif., Sept., 1972.

6.2 RUNWAY VISIBILITY (RVV)

Runway visibility is defined by FMH#1 (4) as simply the "visibility along an identified runway." Now in generally limited use, RVV is one of the oldest of the current generation of automated concepts. It was first put into operation at Arcata, California, for about one year beginning in 1949. Operational use of RVV began in late 1952, using transmissometer measurements from the runway touchdown zone (5).

RVV is usually not reported at any weather station where RVR is reported from one or more runways. An exception is made by FMH#1 when an obscuring phenomenon persistently covers only one portion of an airport. When this condition results in either the RVV-instrumented runway or the RVR-instrumented runway being substantially better than the other, both RVV and RVR are reported. This procedure is intended to alert the user to variations in visibility conditions at the airport.

The algorithm for RVV is the simple conversion from transmittance to visibility, using the basic transmissometer day/night calibration curves (equations 2 and 6). Conceptual visibility targets for RVV are the same as those for the human observer--dark objects during the day and unfocused lights, about 25 candelas, at night. Reportable values of visibility for RVV are about the same as for the human observer (Table 1), with an upper limit of 10 miles. Testing of RVV must be considered coincidental with testing of the transmissometer and development of the transmissometer calibration curves.

Major RVV problem areas include:

- Uncertainties regarding the representativeness of a limited sampling volume as related to runway length,
- Questions about the validity of illuminance and contrast thresholds, and
- Only some independent testing.

6.3 RUNWAY VISUAL RANGE (RVR)

Runway visual range was introduced in the United States at Newark Airport in 1956. Its early development paralleled that of RVV, but today there is international acceptance of RVR. Virtually every nation having an airport equipped with an instrument landing system uses RVR, with perhaps only slight variations from the U.S. technique.

FMH#1 (4) defines RVR for the United States as "a value normally determined by instruments alongside and about 14 feet higher than the center line of the runway and calibrated with reference to the sighting of high-intensity runway lights or the visual contrast of other targets--whichever yields the greater visual range."

The fundamental instrument used for RVR in the United States is the transmissometer (6). Transmissometer measurements are transformed to RVR by a runway visual range signal data converter system (7). Principal inputs to the converter are transmittance, baseline length, day/night status, and the intensity setting of the runway lights. As use of the RVR concept has been extended to the lowest visibility conditions, more reliable and sophisticated systems have emerged. At least one system (8) includes an ambient light sensor to measure and quantify sky brightness to one of four ICAO-recommended values, instead of simple day/night classifications.

The RVR concept in the United States was developed largely as a result of Douglas' early work at the Landing Aids Experiment Station at Arcata in the late 1940's (5). A summary history of the development of RVR can be found in Lefkowitz's and Schlatter's An Analysis of Runway Visual Range (9), from which some of the following material has been synthesized.

At night (and under certain daytime conditions) when the high intensity runway lights are the most prominent targets for the pilot, RVR is derived from:

$$E_t = \frac{I(t_b)^{V/b}}{\left(\frac{V}{5,280}\right)^2} \tag{8}$$

where:

E_t = illuminance threshold (mile-candles),
I = intensity of runway lights (candelas),
t = transmittance,
b = transmissometer baseline (feet), and
V = visual range to appropriate light target (feet).

Under bright daytime conditions when objects contrasted against the sky offer a greater visual range than light targets, RVR is derived from:

$$\varepsilon = (t_b)^{V/b} \tag{9}$$

where:

ε = contrast threshold,
t = transmittance,
b = transmissometer baseline (feet), and
V = visual range to appropriate contrast target (feet).

Inputs to the RVR equations are selected empirical constants that have been derived through experimentation, experience, and some measurement. The inputs are the following:

- ε: The ratio 0.055.
- E_t: 1,000 mile-candles during daylight and 2 mile-candles at night.
- t: A transmissometer measurement integrated over a nominal one-minute period, made along a specified path in the landing/takeoff zone.
- b: The transmissometer baseline. At the present time, usually 250 or 500 feet.
- I: The representative intensity of the high-intensity runway lights. Accepted values are, for step 5, 10,000 candelas; step 4, 2,000 candelas; and step 3, 400 candelas. Step settings 1 and 2 have no validity in RVR.

The change from operational day status to night occurs at an approximate horizontal illuminance of 2 footcandles. The differences between day and night RVR concepts, along with variations in runway light settings, can result in large disparities in RVR at the same transmittance (Figure 12).

RVR is not invariably an automated observation. There have been occasions in the United States and elsewhere when human observers were stationed near the end of a runway to count the number of visible high-intensity runway lights. The distance to the farthest light constituted RVR.

The RVR concept is constantly under review at national and international levels. Elements under consideration include fundamental definitions, sensor height and location, reporting limits, sampling periods, and basic inputs. As an example, the WMO has agreed upon a value of 0.050 for the contrast threshold, while the United States uses 0.055. Net RVR differences are quite small, however.

RVR testing has been both implied and direct. The groundwork for RVR consisted of a broad base of international information and the early development tests at Arcata (5, 9, 10, 11). Additional information was obtained from sensor development and testing at Washington National Airport and at MacArthur Airport, New York, in the mid-1950's (12, 13). Further studies were conducted at the FAA test facility at Atlantic City, New Jersey, in the mid-1960's to analyze modifications to RVR equipment for measurement of low RVR values (14).

Direct tests of RVR were conducted at Atlantic City as part of a program for upgrading terminal weather observations (15). The purpose of the effort was to validate the credibility of the RVR

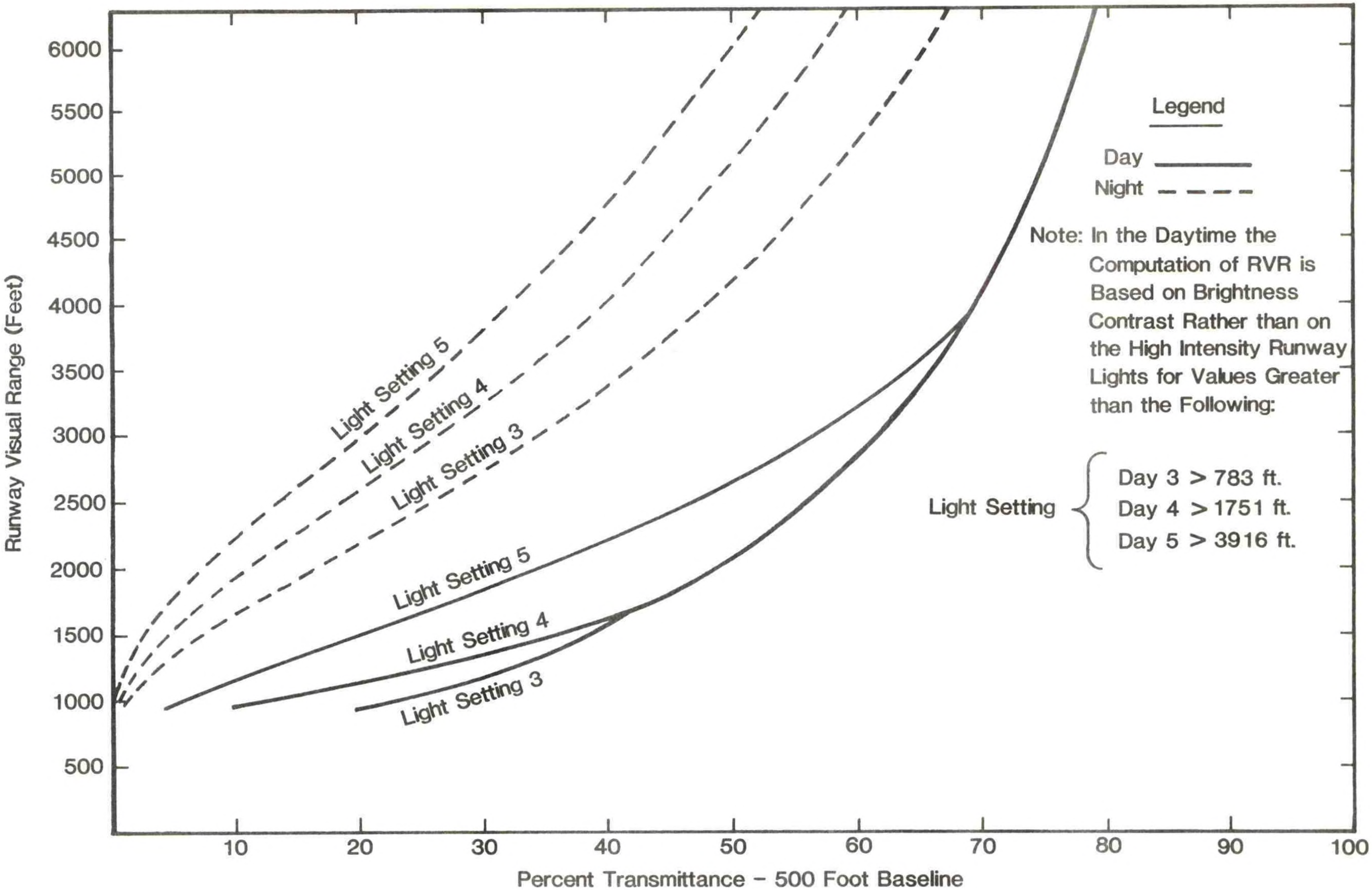


Figure 12. U. S. RVR Calibration Based Upon Runway Light Intensities, Transmittance, and Day/Night

Source: C.A. Douglas and R.L. Booker, Visual Range: Concepts, Instrumental Determination, and Aviation Applications, National Bureau of Standards Monograph 159, Washington, D.C., June, 1977.

system. An effort was made to obtain benchmark data using measurements of RVR based on static human observations of light targets (16). Data acquisition was conducted during 1965-1966, when 30 observers accumulated about 3,200 RVR observations. Observers stood atop a specially instrumented test vehicle located at the center of the Atlantic City Airport instrument runway. Their goal was to count to the farthest runway light sighted under a variety of weather conditions. The count was the human version of RVR. This information, along with coincident transmissometer measurements, runway light settings, background brightness, and general photometric measurements, constituted the test data base.

Analysis of the test data showed a wide range of observer illuminance thresholds. During daytime tests of runway light sightings, about 92 percent of the static human observers had illuminance thresholds equal to or less than the accepted standard of 1,000 mile-candles. At night, about 67 percent had illuminance thresholds equal to or less than 2 mile-candles, the accepted standard. In effect, this meant that 92 percent of the static observers were able to see runway light targets during the day farther than predicted by standard RVR measurements. However, no allowance was made for transmittance of windscreen. At night, 67 percent could see farther than standard RVR.

The test report (16) concluded that differences between observer sightings and RVR are not necessarily the fault of the RVR concept. The primary problem appears to be the inability to standardize the human observer or user. One of the most significant findings was that no single RVR value is exactly correct for a group of observers or pilots. This situation may result partially from the fact that the values of illuminance and contrast thresholds are fixed and represent a practical compromise in the RVR concept, while in actuality threshold values vary between persons and within individuals depending on time and circumstance.

Perceptual variation between observers was pointed up by the results of the Atlantic City tests. During 69 nighttime test observations made over several periods when transmissometer RVR was fairly steady (between 1,600 and 2,000 feet), human visual counts of runway lights differed from the transmissometer 80 percent of the time. Differences ranged from -800 feet to +1,400 feet. Since measured RVR was relatively constant, the source of these differences had to be the human participants (15).

A significant weakness of the Atlantic City tests was the fact that test subjects were static, atop a vehicle; therefore, results only approximated those that might have been obtained from a flight program. No matter how carefully the tests were constructed, the use of stationary observers rather than pilots in a flight cabin environment must be considered a limiting factor.

At a later date, Obers (17) reviewed the relationship between human observations and RVR. He believed that surface human estimates of RVR and those from the pilot's viewpoint differed because of differing axes of illumination with respect to runway lights and variations in the inherent surrounding luminance. These problems were minimized by the construction of the tests at Atlantic City, but although observers counted runway lights from a pilot's approximate height at takeoff at the center/end of the runway, the cockpit environment was not duplicated.

Because of the complexity of RVR both conceptually and operationally, problem areas are highly detailed. They are briefly summarized as follows (18):

- The pilot's visual threshold may only approximate the single fixed values used in the current RVR system. The pilot's vision may be affected by many indeterminate factors, including general health, workload, effect of precipitation and dirt on aircraft windshields, and cabin illumination.

- The pilot's eye level may vary with each approach. Consequently, accepted values for runway light intensity may not be truly representative.

- The condition of runway lights can affect RVR concepts. Lights may be dirty, have reduced output, or even be missing.

- The RVR concept may be limited by the presence of other airport lights, including runway centerline lights.

- A pilot may encounter variations in visibility that are not adequately reported even by multiple transmissometer systems along a runway.

- The transmissometer may not be properly calibrated.

- Pilots may not be aware of the exact nature of RVR. Some may confuse it with slant visual range and use it accordingly. Further, it is not likely that all pilots are aware that RVR is actually a probability rather than the apparent absolute value they are given operationally.

Despite a rather lengthy list of problems, RVR has been an outstanding success within the aviation community. It has virtually replaced prevailing visibility for commercial and military aviation use.

Two final points should be made regarding RVR. Olbers (17) cites Middleton's 1952 comment that the entire system of visibility targets and human estimates of visibility should be discarded. The replacement would be "good instrumental measurements of the extinction coefficients followed by a calculation of a value of interest to the user." Oddie (18) goes a bit further; after a review of some RVR problems, he states, "At this point, a final question may be asked: Will not aircraft soon be able to take-off and land regardless of the visibility or RVR?" Oddie believes the answer is yes.

6.4 AUTOMATIC OBSERVING STATION (AUTOB)

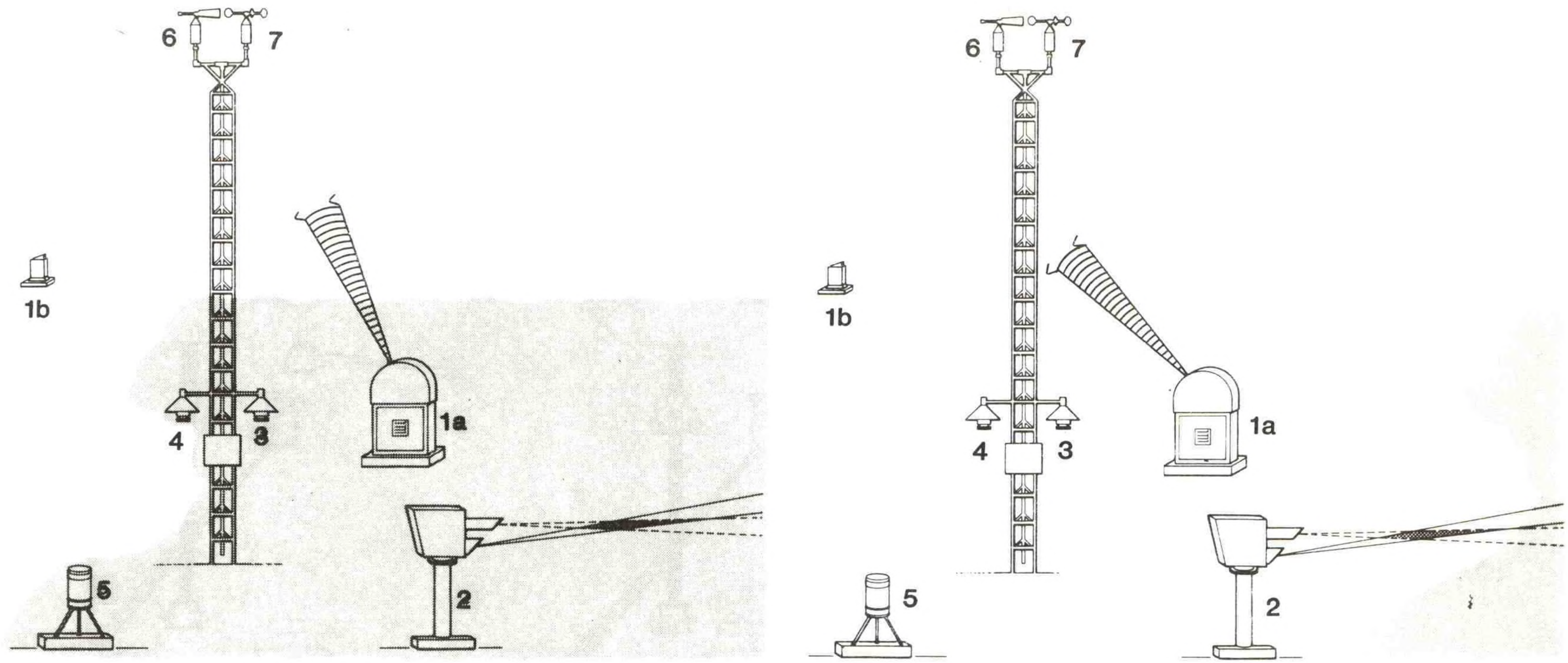
AUTOB is the acronym for automatic observing station. The system measures and processes cloud height to 6,000 feet, cloud amount, precipitation occurrence, temperature, dew-point temperature, wind speed, wind direction, altimeter setting, peak wind, precipitation accumulation data, and an index of visibility (19). The system, already in field operation, is intended for limited-service locations. Although the objectively measured parameters are relatively complete, cloud and visibility algorithms are simplistic. The format for an AUTOB observation is very similar to the human-generated surface weather observation, but there are important differences between the two, particularly for the cloud and visibility elements.

AUTOB visibility is characterized as an index of visibility. It is neither prevailing nor sector visibility. The visibility sensor used is the Videograph, a back scatter type, and the visibility algorithm is the combined day/night calibration curve developed by the NWS (20). There is no difference in index of visibility between day and night. (Note that the index of visibility is not the same as the "visibility index" originally devised for an earlier automated system, the AMOS III-70 (21).)

In the AUTOB station, the index of visibility consists of three digits prefaced by the letters BV (for back scatter visibility). The digits are codes for sensed visibility; they range from 0 (less than 3/4 mile) to 8 (above 7-1/2 miles). The first digit is present visibility, averaged over a three-minute period prior to observation time. The second and third digits describe, respectively, the maximum and minimum values during the past 10 minutes; this information is intended to provide an estimate of visibility variability in the area (Figure 13).

Testing of the AUTOB visibility algorithm (BV) consisted of a field test at Summit, Alaska, and controlled tests at Sterling, Virginia. At Summit, BV was compared to the standard visibility observations made routinely by assigned human weather observers. At Sterling, BV was compared to visibility observations made by "dedicated" test observers. Results of these tests showed good relationships at both Summit and Sterling between current BV and observed prevailing visibility. Of the 132 daylight observations made at Sterling by a dedicated observer, 61 percent differed from the concurrent AUTOB visibility by less than one mile. Eighty-eight percent of the observations agreed within one mile or less. In only 12 percent of the paired observations were there differences greater than one mile. It should be noted that the test observer was co-located with the Videograph, reflecting the manner in which the sensor was originally calibrated. As the distance between the observer and the sensor increases, the magnitude of differences could also be expected to increase (22).

Field performance of AUTOB systems has generally been satisfactory, but certain questions have persisted regarding BV operation. One



(a) (b)

The Maximum and Minimum Visibility Measurements Over the 10-Minute Period Prior to an AUTOB Message are Reported with the Current Visibility Reading and can Reveal Important Fluctuations.

A Patchy Ground Fog Situation is Illustrated Above. The Sky is Clear. As Shown in (b), the Current Visibility is High. However, within the 10 Minutes Prior to this Current Observation, the Visibility has been much Less, as Shown in (a).

Figure 13. AUTOB Reporting of Visibility Fluctuations

Source: National Weather Service, User's Guide to the Automatic Observing Station (AUTOB), Silver Spring, Md., Jan., 1979.

frequent complaint asserts that BV reports are too low. There are several possible explanations for this: mainframe problems, unstable calibration of the Videograph, limitations of the Videograph siting, and users' overexpectations.

Other problem areas for AUTOB include:

- Uncertainties of the combined day/night Videograph calibration,
- Performance during highly variable visibility conditions,
- Satisfaction of FAR requirements,
- Number of sensors,
- Whether the simplistic algorithm really satisfies users' needs,
- Lack of field calibration of the Videograph,
- Reliability of the overall AUTOB system in remote areas, and
- Adequacy of data-checking procedures,
- Effects of absorption, snow and rain.

6.5 AVIATION AUTOMATED WEATHER OBSERVATION SYSTEM (AV-AWOS)

AV-AWOS is the acronym for Aviation Automated Weather Observation System, a comprehensive, multi-sensor system designed to totally automate the surface weather observation. Earlier automated observing systems (RVR, RVV, and AUTOB) produce specialized visibility observations of limited scope. The AV-AWOS concept uses the technique of sensor equivalent visibility (SEV) (23) to process a complex group of measurements from a network of sensors to produce an equivalent of FMH#1-defined prevailing visibility (24). AV-AWOS is the first system that attempts to provide an automated product equating directly to a human observation of prevailing visibility.

The AV-AWOS developmental tests used a triangular network. Back scatter sensors were located at each apex of a triangle whose center was the location for which automated visibility observations were being derived. The center was also the location of the surface weather observer, the standard against which the AV-AWOS visibility observations were compared.

Updated AV-AWOS visibility algorithms were issued as a result of the experiments reported in reference 24 (25). Although the updated versions have not been tested, the differences between them and the original algorithms may be small enough to maintain the significance of the earlier tests. There are three AV-AWOS visibility algorithm options, each intended for slightly different service.

1. <u>Option 1: Single-sensor Visibility Algorithm--Continuous Display Mode (Figure 14)</u>

This is a single-sensor AV-AWOS algorithm designed to be updated every minute on operational airfield displays. It has the capability of detecting and reporting special visibility observations as required by FMH#1.

Sensor preprocessing requires that visibility sensor outputs be converted to the extinction coefficient. The one-minute linearly averaged extinction coefficient is then converted to visibility in miles, using given conversion factors. The algorithm developers believed that by first using the extinction coefficient, it would be easier to relate the outputs of various sensors to make the algorithm sensor-independent.

Direct input to the algorithm is SEV (day and night) in miles. Ten one-minute readings of SEV are linearly averaged and rounded off to reportable values of visibility. These values are directly output as the equivalent of prevailing visibility, unless modified by a subprogram for variability when the visibility is three miles or less. Appropriate checks are included to output "specials" when required. This program has an update frequency of one minute.

2. <u>Option 2: Three-sensor Visibility Algorithm--Continuous Display Mode (Figure 15)</u>

This algorithm satisfies the original AV-AWOS concept that multiple sensors are needed to generate an automated equivalent of prevailing visibility. In this option, three visibility sensors are located at three points around the area of interest. Exact locations are determined by a special site survey prior to the installation of equipment.

This option specifies the same preprocessing as required by Option 1--a one-minute linearly averaged extinction coefficient. One value of the extinction coefficient is obtained from each of the three sensors and then converted to SEV, day or night. Three separate bins then store 10 continuously updated SEV values.

Each bin is averaged and rounded off to a visibility value. Prevailing visibility is the middle value of the three visibilities. Provisions are made if one or two sensors are inoperative, and appropriate subprograms are provided for variable visibility and "specials." An important advantage over the single-sensor algorithm is a subprogram that generates sector visibility using the locations of each sensor. Visibility is updated each minute.

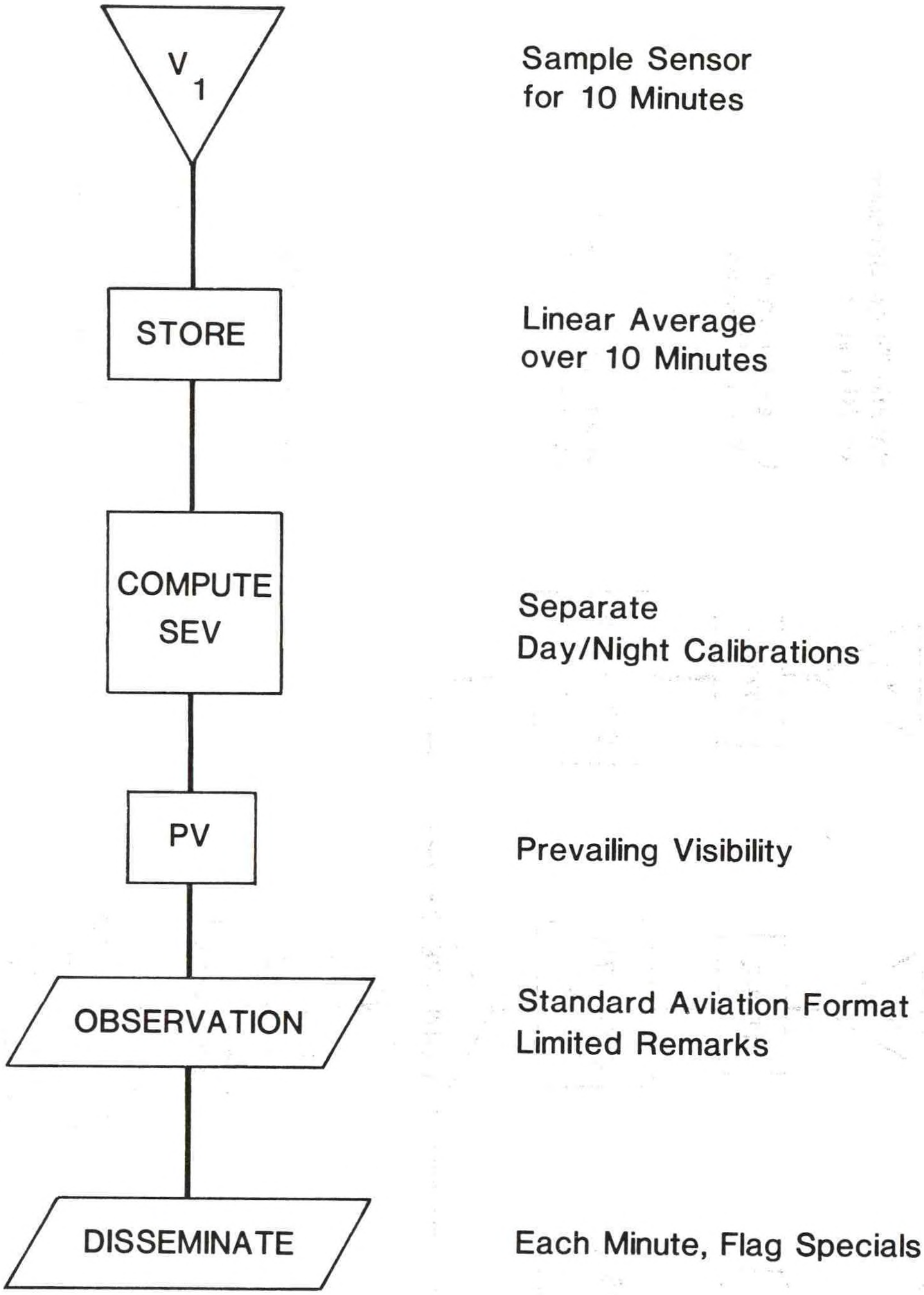


Figure 14. Single-Sensor AV-AWOS Visibility Algorithm (Continuous Display Mode)

Source: National Weather Service, Automation of Visibility Observations: Design Algorithms, Test and Evaluation Division Report No. 5-80, Sterling, Va., July, 1980.

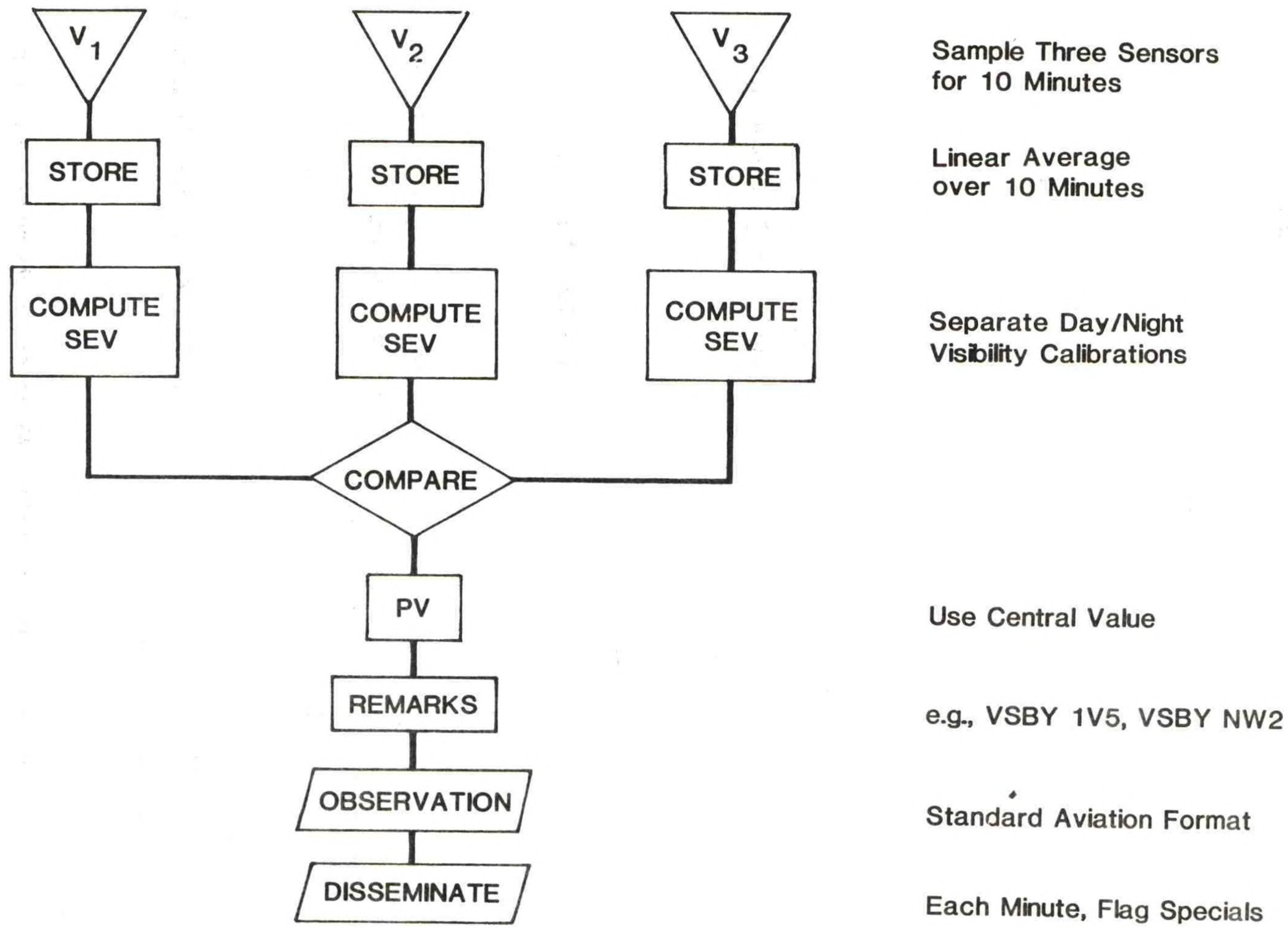


Figure 15. Three-Sensor AV-AWOS Visibility Algorithm (Continuous Display Mode)

Source: National Weather Service, Automation of Visibility Observations: Design Algorithms, Test and Evaluation Division Report No. 5-80, Sterling, Va., July, 1980.

3. <u>Option 3: Single-sensor Visibility Algorithm--Call-up Display Mode (Figure 16)</u>

   This algorithm computes a new output on demand. No sub-algorithms are provided for "specials," and the one for variable visibility is more limited than in Option 1. With these exceptions, the strategy for Option 3 is similar to that of Option 1.

Specific test results of the AV-AWOS algorithm are limited to the original versions. However, since the updated versions reflect those test results, it is likely that their performance would be equal to or better than the original versions.

Tests of AV-AWOS (24, 26) were conducted at typical weather station environments. At Patrick Henry International Airport (PHF), FAA weather observers provided the comparison observations, taking routine visibility observations at ground level. As commonly found in flat terrain, visibility markers were quite limited. Developmental tests were initially conducted at Dulles International Airport (IAD), another flat terrain location. There, NWS observers were located about 35 feet above the ground. Figure 17 shows the test network at PHF, similar to but slightly smaller than that at IAD.

Table 4 shows comparisons between combinations of totally objective AV-AWOS visibility reports. Sensor observations from two of the three network sites were compared with each other. Then, an AV-AWOS visibility observation based on the complete system was compared with a similar observation from one arbitrarily chosen sensor site. Results of comparisons made at both PHF and IAD show consistently high relationships. A lesser agreement results when the objective observations are then compared with subjective human observations (Table 5). The performance of the human observer, of which there have been few or no tests, might be questioned.

Bradley, Lefkowitz, and Lewis (24) also discuss Videograph calibration. They point out that there is a strong relationship between human and Videograph measurements in the presence of hydrometeors. However, during haze, smoke, dust, and the like, Videograph measurements seem to produce visibilities lower than those observed by humans. Past records show that the NWS's Videograph calibration was based largely on a hydrometeor condition--fog (27); lacking weather-type detectors, investigators had recommended a compromise calibration.

A final recommendation from the AV-AWOS tests was that installation of an automated weather system should proceed in a manner typical of other major aviation facilities. First, a period of investigation would be required to define the network configuration. After operation had begun, continued review of performance would be needed.

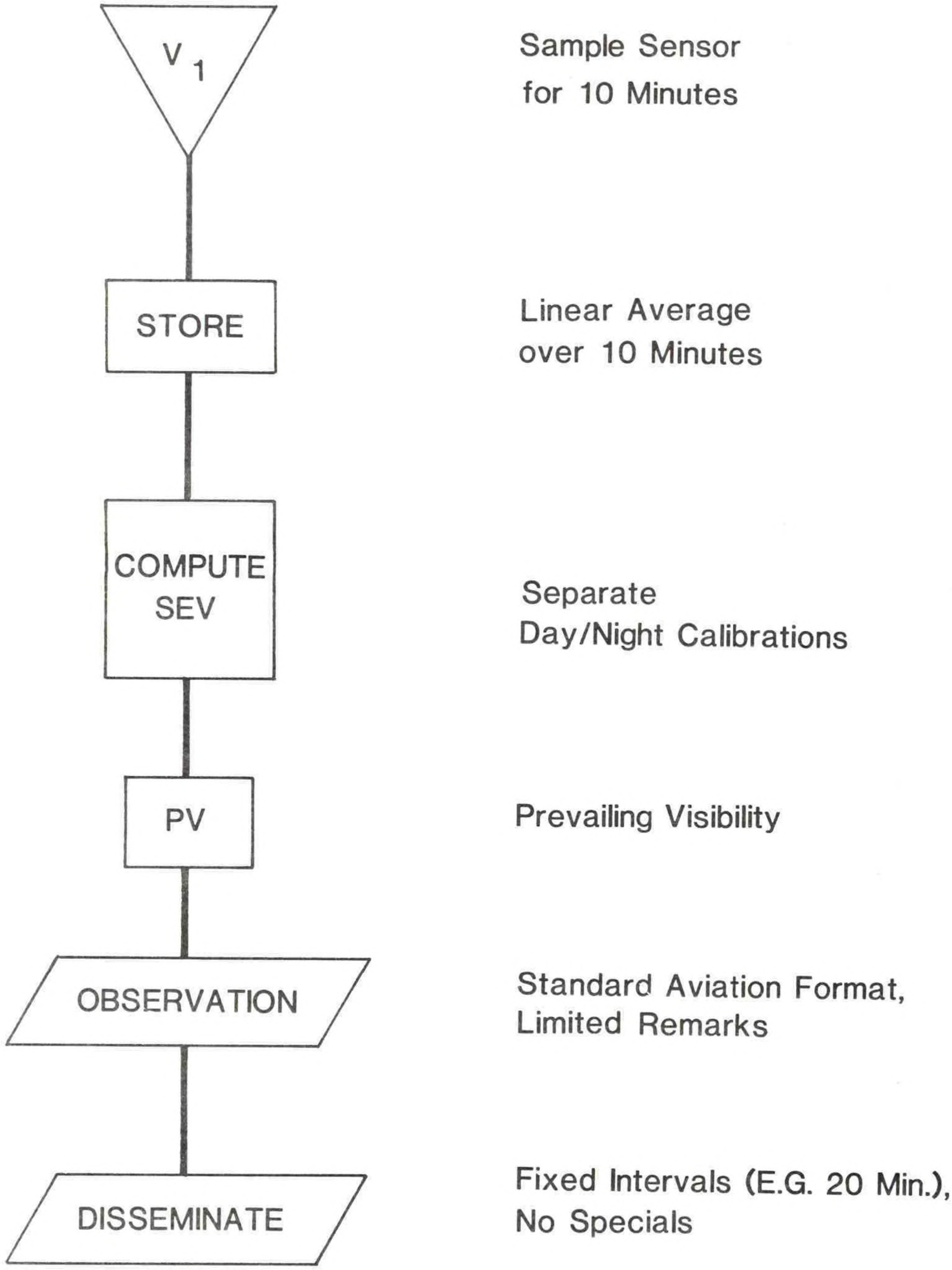
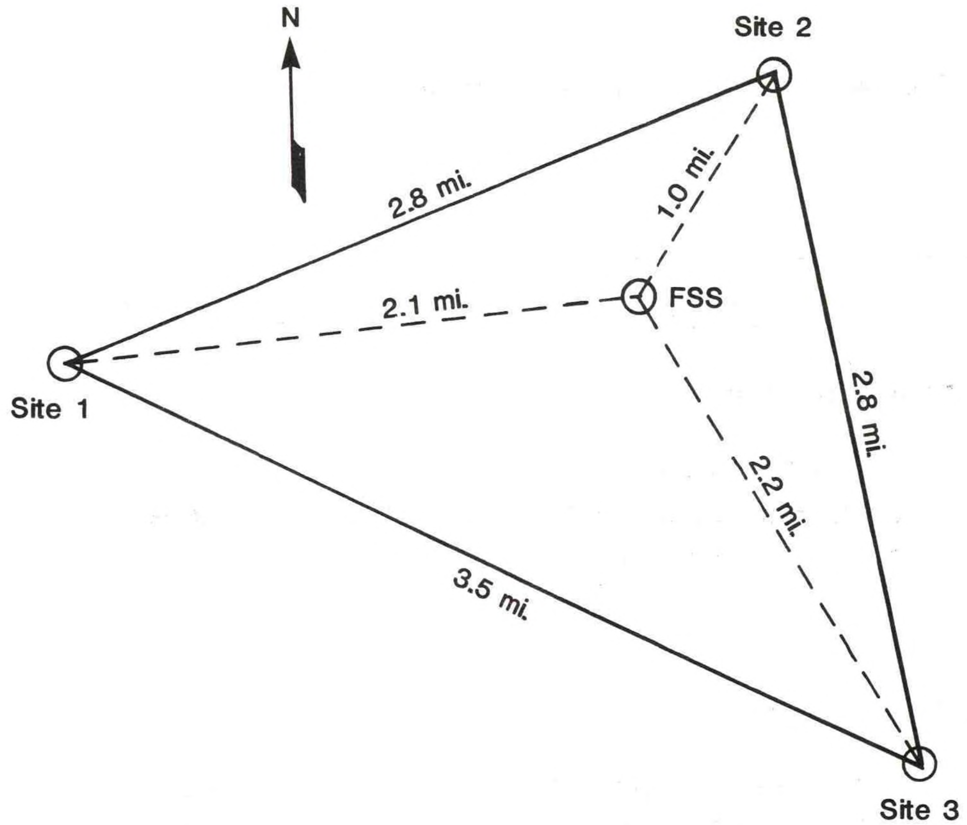


Figure 16. Single-Sensor AV-AWOS Visibility Algorithm (Call-Up Display Mode)

Source: National Weather Service, Automation of Visibility Observations: Design Algorithms, Test and Evaluation Division Report No. 5-80, Sterling, Va., July, 1980.



Site 1–Denbigh–West Site. Near a Heavily Travelled Traffic Intersection, on a Roof with Projector and Detector About 30 ft. above Ground.

Site 2–Kentucky Farms–Northeast Site, Pointing Toward an Open Field. Elevation about 10 ft. above Ground.

Site 3–Hampton Roads Academy–Southeast Site, About 1.2 Miles West of a City Trash Incinerator Smokestack. About 20 ft. above Ground Pointing over a Soccer Field.

Figure 17. Visibility Sensor Test Sites at Newport News, Va.

Source: National Weather Service, Automation of Visibility Observations: Design Algorithms, Test and Evaluation Division Report No. 5–80, Sterling, Va., July, 1980.

Table 4. AV-AWOS Visibility Observations, Sensor vs Sensor

Methods	Agreement ± 1 Mile
1. All Visibility Values:	
2 Separated Sensors-PHF	87 %
2 Separated Sensors-IAD	89 %
Sensor PV/Single Sensor-PHF	92 %
2. Sensor Visibility Below 5 Miles:	
2 Separated Sensors-PHF	90 %
2 Separated Sensors-IAD	90 %
Sensor PV/Single Sensor-PHF	93 %

Source: J.Bradley, M.Lefkowitz, and R.Lewis, Automating Cloud and Visibility Observations, National Weather Service, Test and Evaluations, Division Report No. 2-78, Sterling, Va., Nov., 1978.

Table 5. Visibility Observations, AV-AWOS vs Human Observer

Methods	Agreement ± 1 Mile
1. All Visibility Values:	
Sensor PV/PHF Observer	69 %
Sensor PV/IAD Observer	58 %
2. Observer Visibility Below 5 Miles	
Sensor PV/PHF Observer	80 %
Sensor PV/IAD Observer	72 %
3. Sensor Visibility Below 5 Miles	
Sensor PV/PHF Observer	57 %
Sensor PV/IAD Observer	45 %

Source: J.Bradley, M.Lefkowitz, and R.Lewis, Automating Cloud and Visibility Observations, National Weather Service, Test and Evaluation Division Report No. 2-78, Sterling, Va., Nov., 1978.

The AV-AWOS algorithms represent a clear breakthrough in the automation of surface weather observations. But several problem areas still remain:

- A better way must be developed for assessing the performance of automated observations. Human observations of visibility, although a standard, are still subjective.
- AV-AWOS algorithms are based on a limited amount of data. Further development and testing at various locations with other instruments might be considered.
- Optimum network size and configuration have not yet been fully specified. Further tests might reveal that there are no optimum values, but tailoring to individual sites is needed. Procedures for such tailoring must be developed.

6.6 SLANT VISUAL RANGE (SVR)

There is no "official" definition of slant visual range (SVR). For purposes of this report, SVR may be considered the distance at which a pilot on the approach path first establishes contact with specified lights (either approach or high-intensity runway lights). This distance can be reported at the time of contact with specified target lights as actual range from pilot to target or as the distance from ground to pilot.

Although a considerable amount of research has been conducted on SVR, the requirement for it sometimes appears vague. A committee recently considering the matter (28) concluded that the need for SVR was not firmly established. In fact, the need for SVR decreases as landing operations move toward very low visibility conditions. Also, the cost of developing and testing SVR may be too high for the value received.

The development of the transmissometer and the rotating-beam ceilometer permitted relatively high-frequency measurements of visibility and clouds for the first time. Field experiments indicated that the transmissometer/ceilometer combination offered a sound method for remote measurement of weather in the approach zone. A recommendation quickly followed that a program be conducted to develop new or improved methods of estimating SVR.

The fundamental concept of SVR is illustrated in Figure 18. SVR is measured not necessarily along the glide slope but, instead, over the cockpit cut-off angle to the designated target. The target usually determines the particular type of SVR. For example, sighting the threshold lights at the end of the runway is considered threshold contact height (TCH). Approach light contact height (ALCH) concerns contact with the high-intensity approach lights that precede the runway. In this concept, the sighting of a string of five approach lights was thought necessary to give the pilot adequate guidance. Note that TCH and ALCH are not distances to the

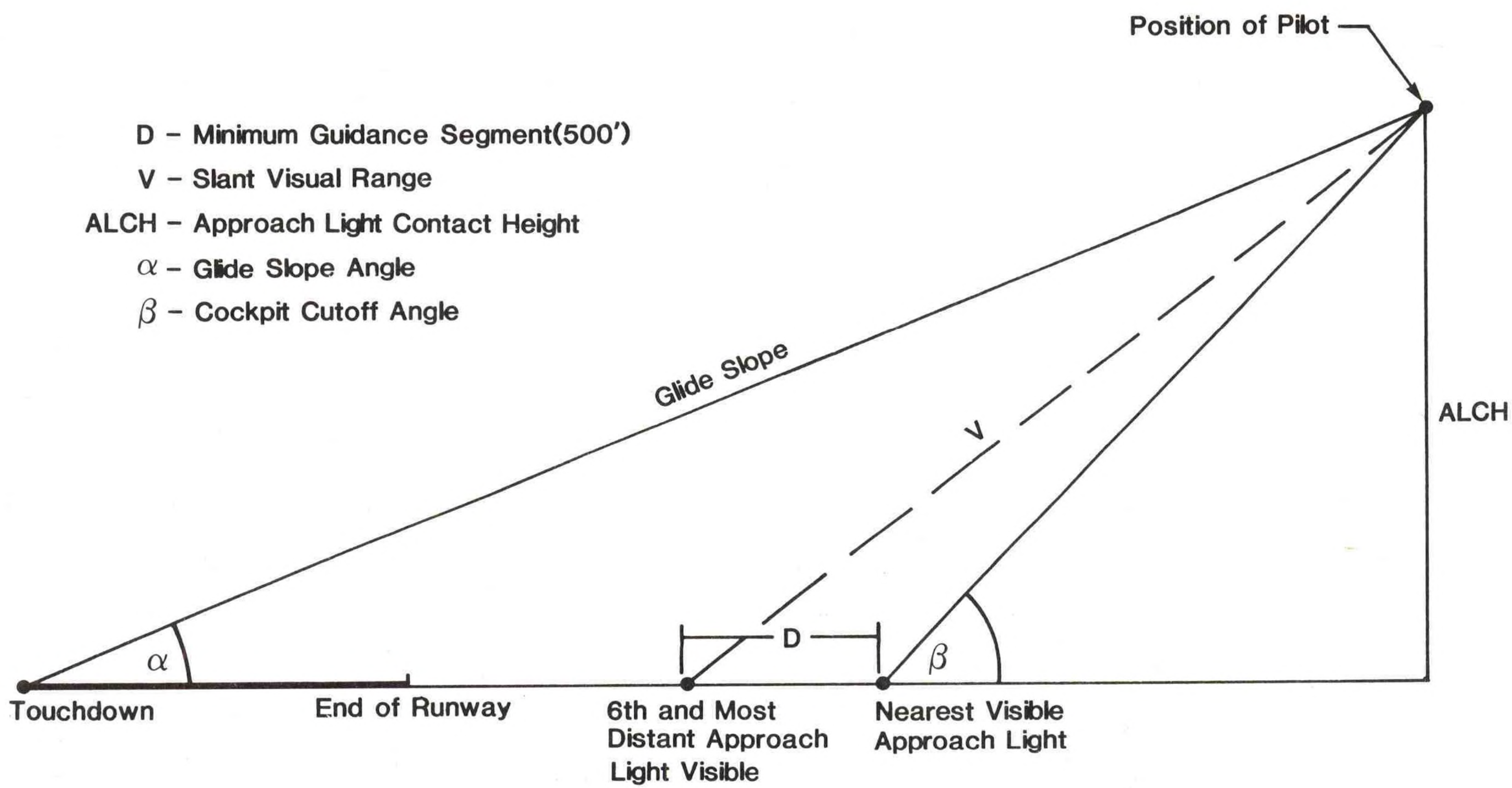


Figure 18. Geometry of SVR and ALCH

Source: M.Lefkowitz, Studies in the Field of Approach Visibility Measurements and Instrumentation, Federal Aviation Agency, Final Report, Project No. 202-2-1X, Atlantic City, N.J., April, 1962.

target; rather, they are the heights above the ground at which the pilot makes eye contact with the light targets (29).

Some of the earliest tests of SVR concepts (12, 13) led to the conclusion that "meteorological observations, as routinely made at present, do not accurately indicate conditions the pilot will experience. . . ." As a result, a development and test program was planned for Newark Airport in the late 1950's. The objective at Newark was to devise a system for quantitatively describing approach visibility conditions to pilots and air traffic controllers (30). First results indicated that the end-of-runway green threshold lights were not adequate targets in the presence of high-intensity approach lights. Using surface-based instrumentation (a rotating-beam ceilometer and transmissometer), an ALCH system was developed. The ALCH output took the form of dual probability levels to indicate the height at which a pilot would first see a guidance segment of the approach light string. The two probability levels were thought to be useful information for the approaching pilot. A detailed analysis of 2,375 instrument approaches was carried out over 23 months to develop the ALCH equations.

The ALCH system was tested again at Atlantic City in the early 1960's. A more limited data sample was obtained, but results generally supported the system developed at Newark. However, ALCH with its two probabilities was not implemented. The probability concept was not popular, and RVR, which had also just emerged, was more acceptable. What had not been made clear to users was that the single value of RVR was, in fact, also a probability value.

Another limitation of the original ALCH concept was the ground-based instrumentation, which generally assumed uniform visibility conditions with height. However, despite limitations and difficulties, SVR continued to be an attractive goal. In 1968, an attempt was made to investigate the use of a pulsed ruby lidar in such a system (31). Although instrumented data verification was limited, the investigators concluded that their lidar system had great potential.

Another approach was taken at the Naval Ammunition Depot at Crane, Indiana (32). Atmospheric modeling, scattering concepts, and sophisticated statistical techniques were used to develop several candidate ALCH systems. At a later date, the Crane group conducted tests of their systems at the FAA experimental facility at Atlantic City (33). Instrumentation included transmissometers installed at several different levels of two meteorological towers. The investigators concluded that surface-based RVR transmissometers were inadequate; it was necessary to sample the vertical variations of the atmosphere for an accurate measure of SVR.

An ambitious SVR experiment was conducted at Travis Air Force Base, California (34). There, a pulsed ruby lidar and four transmissometers were installed on towers and aligned along horizontal and slant paths. Arrays of passive reflectors were used to obtain some measure of attenuation. The investigators concluded, with some qualification, that a lidar technique had good potential as a practical system for the measurement of SVR.

More recent work has included forward scatter sensor measurements of SVR (35) and the development of a remote tower SVR system (36). But there is currently no operational SVR system in the United States. The question of the need for SVR is perhaps best addressed by Douglas, who commented that what is needed is a forecast of RVR--not just an observation of current SVR, which the pilot normally makes at decision height during a landing approach (10).

6.7 REMOTE VISUAL METHODS

There has always been a feeling among researchers that while visibility instrumentation might be perfected, remote human visual observation methods would still be useful. The advent of television provided a great boost for this contention.

Some of the earliest practical remote TV experiments were conducted by the U.S. Weather Bureau at Washington National Airport in 1952 (37). The objective was to compare human estimates of visibility made by an end-of-runway observer with a TV image from a camera oriented in the same direction as the observer. Using up-to-date TV equipment of that period, investigators concluded from daytime tests that good agreement could be achieved between TV and human observers. Nighttime results indicated that the human eye was more sensitive than the TV system. Unfortunately, the tests were marred by too few low-visibility periods.

Some years later, Gavrilov concluded that TV was still not ready for such work (38). He wrote that insufficient contrast sensitivity, lack of stereoscopic features, poor resolving power, and other problems left TV visibility applications still in an experimental stage.

Almost a decade later, the NWS conducted an experiment involving TV images of visibility targets (39). Observers were asked to estimate prevailing visibility based on video recordings of limited black-and-white TV scans at Washington National Airport. Inexpensive, off-the-shelf TV equipment was used for the tests. After analyzing the results, researchers concluded that the TV concept had great promise. They suggested that color would greatly improve results, along with observer-controlled panning, selectable lenses, continuous monitoring, and observer training.

Improved results were achieved by a later experiment using better-designed equipment (40). Here, the visibility observations were restricted to weather conditions in a mountain pass. A remote, black-and-white, slow-scan video system was used to view the pass, and the display was made available to weather briefers and pilots. Natural terrain features were used as visibility targets. "Good" and "bad" visibility conditions were readily recognized with this system, but more marginal conditions could be portrayed only with varying degrees of success. The investigators concluded that high-contrast TV targets were needed.

6.8 SINGLE vs MULTIPLE SENSOR ARRAYS

As described earlier in this section, there are several automated visibility observing techniques that offer great promise. Each, of course, requires some form of visibility sensor. But the number of sensors needed to adequately portray visibility conditions has not yet been determined.

Early RVR investigators reached the conclusion that RVR determined from a transmissometer at runway touchdown is not always representative of the visual range encountered by a pilot during landing, roll, and takeoff (29). Follow-up work confirmed the need for at least three transmissometers along a runway and even more during special conditions (16).

There are two basic controlling influences on the number of sensors needed to adequately report visibility conditions. One is management's decision concerning the extent of resolution and representativeness required, and the other is the natural variability of visibility. Variation of visibility is discussed in the next section.

SECTION 6

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7.0 VARIABILITY OF VISIBILITY

Visibility instruments are calibrated with the assumption that the local visibility is homogeneous. Standard surface visibility observations generally assume that the observer's view is representative of a relatively large area. But in fact, visibility is not often stable or uniform. Lack of uniformity in visibility creates problems for automation because expensive multiple-sensor systems must be considered. And there is always the pilot who radios back that the runway is clear--it is the observer who is in fog!

Variation of visibility is the combined effect of variations in time and space, advection past the sensor, mechanical effects, and physical characteristics of the visibility-limiting phenomena. These elements cannot be separated and thus are usually measured as a single, ever-changing aspect of weather at the point of observation.

7.1 VARIABILITY OF VISIBILITY NEAR THE GROUND

Although variations in visibility had been documented through conventional human observations and during the development of the transmissometer, it was not until the field deployment of the transmissometer that researchers determined the great extent and frequency. Morton and Haig (1)* used the sensors at Newark Airport to examine variability. They considered the problem of cost for multiple visibility sensors needed to increase representativeness, and they recommended the selection of one representative site rather than multiple installations as a cost-effective solution. In statistically comparing data from a transmissometer at the end of a runway and another near the geographic center of Newark Airport, they found that the variances (the mean-square deviations from the mean) of simultaneously measured samples of transmittance at the two sites were not statistically equal. Although the means of the end-of-runway and center-field measurements did not differ significantly, differences in individual measurements could be high. Perhaps their most important conclusion was that the sensors should be located as near as possible to the region where the measurement would be of operational importance. For example, if a report of RVR is required for the approach zone, it should be measured at that point.

Similar conclusions were reached as a result of more extensive and better instrumented tests at Atlantic City (2). Data were obtained and analyzed from five airfields across the United States. The investigators found RVR differences along a runway that were as great as 2,000 feet. They concluded that at least three transmissometers should be installed along a runway at touchdown, midpoint, and rollout, and perhaps even more at airfields having special problem areas.

*See references at end of chapter.

Jones (3) reviewed several published reports concerning variations of visibility. In one small series of measurements, when visibility was below about one-half mile and patchy, 40 percent of the visibility measurements changed upward or downward by about 10 percent or more in the succeeding four minutes and by 20-30 percent or more in 20 minutes. In a significant number of cases (5-10 percent), visibility changed by 30 percent or more in only four minutes. Jones reported that RVR in the range of 1,200-3,600 feet could change at a rate of 330 feet per minute. Twenty-three percent of one test data set showed RVR at runway threshold to be between 1,200 and 3,600 feet, while RVR at runway center-point was below 1,200 feet. On one occasion when the threshold RVR was 2,400-2,600 feet, RVR at runway center was 330-590 feet. Jones emphasized that RVR variations of these relatively high magnitudes have occurred at London, and probably at other locations as well, over airport-significant distances: horizontal distances of the order of 4,000 feet (the distance between threshold and center-point) and 4,800 feet (the distance between parallel runways).

Ito investigated transmittance at Tokyo to determine to what extent measurements at one site at an airfield are representative of a larger area of the field (4). He found cases indicating that changes in transmittance could be "slow and rapid, small and large, periodic and aperiodic." In one extreme case, Ito measured a change in transmittance from 0 to 87 percent within one minute. This rate of change is really not unusual, however. It can be experienced when a sharp-edged fog bank recedes or advances. The rate of change in such cases is limited only by the response time of the visibility sensor.

George (5) relates rapid visibility changes to micro-fog volumes embedded in a meso-fog volume--somewhat like "noodles in the soup." He writes that these fog element are denser, cloudlike discontinuities that sometimes appear to roll or to translate horizontally through a larger fog volume. One set of observations indicated that fog element lengths were less than 250 feet as they moved past test transmissometers. George contends that the distribution of fog element lengths is useful information in the design of optimum instrument configurations for automated visibility systems.

Extensive tests of visibility variability at airfields were undertaken by the Air Force using forward scatter sensors. Such sensors were located along a runway at Hanscom Field, Bedford, Massachusetts. In a report, Chisholm and Kruse (6) discussed tests that analyzed time and space variability during four classes of visibility restrictions--rain, snow, radiation fog, and advection fog. These results, too, showed that the variability of visibility in time and space is sufficient to justify more than one automated measurement along a runway. Variability in both space and time was significantly greater in radiation fog than in advection fog, rain, or snow situations. Variation of visibility with time was greatest in radiation fog and least in rain. The authors found that some earlier statistics developed for transmissometer measurements differed somewhat for forward scatter sensor data. They also arrived at the same conclusions regarding number of visibility sensors along a runway as did earlier researchers (2)--that at major airfields the configuration should include at least three sensors along the runway.

Changes in local fog density, and thus in visibility, were noted during an attempt to develop short-term forecasts of visibility at Atlantic City, (7, 8). The investigators noted that there was considerable change in fog density as the fog moved through a mesonetwork of transmissometers. Thinning was typical when the fog moved inland with an onshore flow of air. In some cases, low visibility improved rapidly in coincidence with the forward edge of a precipitation area. The forecast methods were not completely successful, due to several factors. One reason was that a considerable degree of fog formation or dissipation frequently occurred within a short time interval and was not immediately detected by the visibility sensor network.

7.2 VARIABILITY OF VISIBILITY WITH HEIGHT

Visibility varies not only horizontally, but also with height. There may be gradual or sharp variations with height, depending on the weather pattern and the visibility-limiting phenomena. Consider, for example, the perplexity of the B747 pilot who sits higher than the top of the ground fog layer while the observer at 6 feet above ground and the transmissometer at 14 feet report extremely low visibilities.

Problems related to variation of visibility with height have been recognized in changes to FMH#1 (9). Instructions require that if either tower or surface visibility is less than four miles, the lower of the two is reported in the body of an observation and the higher in the remarks section. Surface visibility is always reported in the body of an observation whenever tower visibility is four miles or more.

Some significant patterns of visibility variation with height were noted during the development of a tower SVR system (10). Heights in these cases were 200 feet or less. It was noted that during a period of moderate rain, there was very little change in visibility with height. During a period of advection fog, however, there was a significant lowering of visibility with height. Fog density also decreased with height during these tests. In fact, Lewis (11) found that predictions of SVR were most accurate when the visibility decreased with height. His measurements were made at 100, 124, and 155 feet above ground.

Other investigators (6) found higher frequencies of reduced visibility with increasing height above ground. During a limited data acquisition period, they found that visibilities greater than 1,300 feet existed 65 percent of the time at a 148-foot tower level, as compared with 78 percent at a 98-foot tower level and 90 percent near ground level. One conclusion the authors reached is that visibility lower than 1,300 feet can be expected at the 148-foot tower level about 25 percent of the time when runway visibility is above 1,300 feet. Another important conclusion is that the vertical variability of visibility is greater than the horizontal variation in both rain and fog.

SECTION 7

BIBLIOGRAPHY

1. Morton, W. C. III and Haig, T. O. Variations of Atmospheric Transmissivity and Cloud Height at Newark. Air Force Cambridge Research Center Report No. AFCRC-TN-57-613, Air Force Surveys in Geophysics No. 91, Bedford, Mass., Jan., 1958.

2. Schlatter, E. E. and Lefkowitz, M. Evaluation of MultiTransmissometer Systems. Environmental Science Services Administration, SRDS Report No. RD-68-49, Atlantic City, N.J., Aug., 1968.

3. Jones, R. F. "Time and Space Variations of Visibility and Low Cloud Within the Approach Control Area." Aeronautical Meteorology, World Meteorological Organization, Technical Note 95, Geneva, Oct., 1969.

4. Ito, H. "Time and Space Variation in Meteorological Elements in the Aerodrome and Its Vicinity." Aeronautical Meteorology, World Meteorological Organization, Technical Note 95, Geneva, Oct., 1969.

5. George, D. H. "Estimates of Fog Element Length." Journal of Applied Meteorology, Vol. 11, No. 5, Aug., 1972.

6. Chisholm, D. A. and Kruse, H. The Variability of Airfield Visibility: A Preliminary Assessment. Air Force Cambridge Research Laboratories Report No. AFCRL-74-0027, Environmental Research Paper No. 462, Bedford, Mass., Jan., 1974.

7. Hage, K. D. and Wilson, J. W. Analysis of the Variability of Low Clouds, Fog, Wind, and Rain in the Atlantic City Mesonetwork. The Travelers Research Center, Inc., Technical Note, Contract No. FA-66-WA-1536, Hartford, Conn., May, 1967.

8. Entrekin, H. D., Wilson, J. W., and Hage, K. D. "Evaluation of the Atlantic City Mesonet for Short Range Prediction of Aviation Terminal Weather." Journal of Applied Meteorology, Aug., 1969.

9. Departments of Commerce, Defense, and Transportation. Federal Meteorological Handbook No. 1. 2nd ed., Washington, D.C., Jan. 1, 1979.

10. Geisler, E. B. Development and Evaluation of a Tower Slant Visual Range System. Air Force Geophysics Laboratory Report No. AFGL-TR-79-0209, Instrumentation Paper No. 281, Hanscom AFB, Mass., Sept., 1979.

11. Lewis, W. Comparison of Slant and Runway Visual Range Relationships for 100, 124, and 155 Feet. Federal Aviation Administration, Report No. FAA-RD-77-191, Washington, D.C., Apr., 1978.

8.0 OVERVIEW OF PAST VISIBILITY STUDIES

Appendices B and C are bibliographies of the major studies that contributed directly to this report or that would be of interest to the reader. Along with most of the citations in Appendix B are comments that briefly highlight the report and, where appropriate, identify weak areas. This section is intended to be an overview of some of the more important points observed during the preparation of this report.

"Modern" visibility research extends back through the last half-century. Each of the many published reports has contributed to later R & D efforts. Despite extensive work through these years, however, it is interesting to note that there is still no totally adequate solution to obtaining fully satisfactory visibility observations, either human or automated.

Several studies used human observations as a standard. In some cases, routine surface visibility observations were used as a measure of performance of a system or sensor being tested. Nathan M. Reiss, writing in the January 1980 Bulletin of the American Meteorological Society, has perhaps the best comment on such usage: "Fewer meteorologists than ever before have firsthand knowledge of the routinely taken weather observations that form the backbone of our meteorological data base. Furthermore, visibility and wind data are coming into increased use by nonmeteorologists who have little understanding of how the observations are made or how the numbers are processed."

Reiss goes on to write, "The method by which observations are really made should be available to the user. I would add . . . that either the rules for making observations be changed to conform to actual practice, or that more vigilance be exercised to assure that observational practice is in accordance with the rules."

In other studies, it was necessary to use human observations as a standard to determine differences between a new observation product (AV-AWOS, for example) and current practice. It is interesting to note the many multilevel tests given new concepts such as RVR and AV-AWOS, both of which attempt to equate a form of human observation. Yet of all the major studies synthesized for this report, none subjected the standard surface observation of visibility to vigorous testing. For the future, blind tests of routine visibility observations might be considered. One to three dedicated observers could take observations of visibility simultaneously with a duty weather observer who is unaware of the tests. Weather conditions and visibility targets should be identical. Not until such tests are made can we gauge the true performance of a commonly accepted standard.

Middleton observes that the theories of visibility are well grounded; later studies appear to be more concerned with practice than with advancing theory. He also feels that the research work that established thresholds for the eye should be accepted, although he acknowledges the limitation that such data were obtained exclusively from young test subjects. However, there continue to be questions about the values of contrast and illuminance thresholds, which are important in applications of Koschmeider's Law and Allard's Law and in areas of visibility that rely upon these concepts. Fixed values are used in RVR, for example, but it is likely that these values actually vary with time and among pilots. An effort using state-of-the-art instrumentation might be undertaken not only to verify earlier work but to examine the variation of such thresholds in actual events such as landing an aircraft during low visibility.

Many assumptions are made during tests of visibility concepts. Most are adequate, but several appear to be weak or not fully considered; these include local scattering, the varying position of the sun, variation in sky and horizon brightness during a variety of realtime situations, target light intensity, and target size, shape, color, and distribution about the horizon.

Most studies appear to be limited by a perennial problem: restricted time and funds. As a result, the generalization of findings is hampered. For example, although the AV-AWOS concept is promising, no definitive work has been completed regarding data network size or configuration. RVR, too, despite its wide acceptance, might be improved by using a larger number of sky brightness conditions and supplemental measurements of photometric conditions along the runway. As one example, RVR does not consider the limitations placed on a pilot landing into the sun.

Visibility instrumentation has been a popular subject for published reports. Various sensors have been developed, tested, and favored, although none has emerged without some limitations. The forward scatter visibility sensor appears to be a favorite at this time but is not yet universally accepted. Many sensor-versus-sensor comparisons have been conducted, but these are often limited by too few sensor types and geographical locations. There appears to be no comprehensive study that documents sensor-versus-sensor tests and includes comparisons with auxiliary instrumentation, such as brightness sensors and telephotometers, and dedicated observers.

Variability of visibility has a major impact on weather observations and sensor measurements. Some reports recommend a larger number of sensors to cope with variable conditions, although costs are increased by multiple sensors. So far, no definitive study has categorically identified the optimum number of sensors for coping with the largest variety of situations.

Although almost all visibility research has been dedicated to identifying conditions for flight personnel, most recent efforts have been static-based. Few, if any, modern studies have used pilots in a natural cockpit environment during flight, takeoff, and landing as a major component of the program.

Most of the earlier studies reviewed for this report pursued general solutions. Theory was refined, and some general approaches were defined. But the instrumentation of that period was relatively unsophisticated by today's standards. More recent studies have tended to focus on more limited goals. Findings outside those specific goals are usually recommended for later study, but they are rarely funded and undertaken. Today's instrumentation and computer methods represent major advances over those available to earlier researchers, but application to old and new problems outside of immediate goals is limited.

APPENDIX A

GLOSSARY

Absorption: The process in which incident radiant energy is retained by a substance. (Ralph E. Huschke, ed., Glossary of Meteorology)

Absorption coefficient: A measure of the amount of normally incident radiant energy absorbed through a unit distance or by a unit mass of absorbing medium. (Huschke)

Airlight: Light from sun and sky that is scattered into the eyes of an observer by atmospheric suspensoids (and, to a slight extent, by air molecules) lying in the observer's cone of vision. Airlight reaches the eye in the same manner in which diffuse sky radiation reaches the earth's surface. (Huschke)

AL: Allard's Law. An equation relating the illuminance produced by a source of intensity on a plane normal to the line of sight at a specified distance from the source, and the atmospheric transmissivity. (C. A. Douglas and R. L. Booker, Visual Range: Concepts, Instrumental Determination, and Aviation Applications)

ALCH: Approach light contact height.

Attenuation: In physics, any process in which the flux density (or power, amplitude, intensity illuminance, etc.) of a "parallel beam" of energy decreases with increasing distance from the energy source. Attenuation is always due to the action of the transmitting medium itself (mainly by absorption and scattering). It should not be applied to the divergence of flux due to distance alone, as described by the inverse square law. (Huschke)

AUTOB: Automatic observing station.

AV-AWOS: Aviation Automated Weather Observing Station.

Background luminance: The brightness of the background against which the visibility marker is viewed. (Huschke)

BV: Back scatter visibility.

Candela (cd): The internationally accepted unit of luminous intensity.

Cone of vision: The imaginary conical surface whose apex is at a given observer's eye and whose solid angle is exactly filled by whatever object the observer is viewing. (Huschke)

Contrast: The ratio of the apparent luminance of a target minus that of its background to the apparent luminance of the background. (Huschke)

Extinction: The attenuation of light; that is, the reduction in illuminance of a parallel beam of light as the light passes through a medium wherein absorption and scattering occur.

Extinction coefficient: A measure of the space rate of diminution, or extinction, of any transmitted light; thus, it is the attenuation coefficient applied to visible radiation. (Huschke)

FAA: Federal Aviation Administration.

FAR: Federal Aviation Regulation.

FMH#1: Federal Meteorological Handbook No. 1.

Hygroscopic: A marked ability to accelerate the condensation of water vapor. (Huschke)

IAD: Dulles International Airport, Chantilly, Virginia.

ICAO: International Civil Aviation Organization.

Illuminance threshold, visual threshold, threshold illuminance: The minimum illuminance at the eye required to make a light source visible. (Douglas)

KL: Koschmeider's Law. An equation for daytime visibility that relates the apparent contrast of an object viewed against a sky or fog background, its inherent contrast, and atmospheric transmissivity. (Douglas)

Luminance: Brightness; a measure of light. (Huschke)

Luminance contrast threshold, contrast threshold, threshold contrast: The minimum luminance contrast at which a target is visible against its background under stated conditions. The contrast threshold is not a constant but is a function of the angular size of the object, the luminance of the background, the criteria that are used to determine if the object is "visible," and the observer's knowledge of the location of the target. (Douglas)

NWS: National Weather Service.

PHF: Patrick Henry International Airport, Newport News, Virginia.

APPENDIX A
cont'd.

Prevailing visibility: The greatest visibility equalled or exceeded throughout at least half the horizon circle, which need not necessarily be continuous. (FMH#1)

PV: Prevailing visibility.

RVV: Runway visibility. The visibility along an identified runway. (FMH#1)

RVR: Runway visual range. In the United States, a value normally determined by instruments located alongside and about 14 feet higher than the centerline of the runway and calibrated with reference to the sighting of high-intensity runway lights or the visual contrast of other targets--whichever yields the greater visual range. (FMH#1)

Scattering: The process by which small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions.

Scattering coefficient: A measure of the attenuation due to scattering of radiation as it traverses a medium containing scattering particles. (Huschke)

Sector visibility: The visibility within a specified portion of the horizon circle. (FMH#1)

Surface visibility: The visibility determined from the usual point of observation. (FMH#1)

SVR: Slant visual range.

TCH: Threshold contact height.

Tower visibility: The visibility determined from the control tower when the surface visibility is determined from another location; e.g., the weather station. (FMH#1)

Transmissivity: Transmittance for a unit distance within a light-transmitting medium. The unit of length must be stated although the term is dimensionless, remaining in the transmissometer light beam after passing through a unit thickness of the baseline sampling path.

Transmittance: The ratio of the transmitted radiant or luminous flux to the incident flux. It may be considered as the ratio of the flux from a source received incident on a receptor (which may be the eye) after passing through a medium without refraction, to that which would be received if the medium were removed. (Douglas) For transmissometer application, the fraction of luminous flux remaining in the transmissometer light beam after passing through the entire baseline sampling path.

APPENDIX A
cont'd.

Variable prevailing visibility: A condition when the prevailing visibility rapidly increases or decreases by one or more reportable values during the period of observation. (FMH#1)

Visibility: In United States weather observing practice, the greatest distance at which it is just possible to see and identify (a) in the daytime, a prominent dark object against the sky at the horizon, and (b) at night, a known, preferably unfocused, moderately intense light source. (Huschke) Also, the greatest distance at which selected objects can be seen and identified. (FMH#1)

WMO: World Meteorological Organization.

APPENDIX B

BIBLIOGRAPHY OF PUBLICATIONS CONTRIBUTING DIRECTLY TO THIS REPORT OR OF IMPORTANCE TO THE READER

Where appropriate, comments have been added to the citations.

Blackwell, H. R. "Contrast Thresholds of the Human Eye." Journal of the Optical Society of America, Vol. 36, No. 11, Nov., 1946.

An important contribution to the subject of contrast thresholds. This report describes the laboratory work done at the Tiffany Foundation during the late World War II years. In a carefully controlled experiment of great magnitude and thoroughness, women observers seated in a static environment viewed contrast brightness targets. More than 2 million observations were made of uniform circular visual targets. Blackwell's results are considered to be of superior, benchmark quality and are often extrapolated to field conditions. Perhaps, though, the results should be verified today using a wider range of test observers and advanced, state-of-the-art photometer equipment.

Bradley, J., Lefkowitz, M., and Lewis, R. Automating Cloud and Visibility Observations. National Weather Service, Test and Evaluation Division Report No. 2-78, Sterling, Va., Nov., 1978.

This report discusses the testing and evaluation of AV-AWOS, a system designed to produce the automated equivalent of FMH#1's definition of clouds and visibility. Perhaps the greatest weakness of this study was the necessary use of routine weather observations at the test site as the standard against which the automated products were measured. Since there is little in the literature regarding performance of the routine weather observer, the standard may be incomplete. Further investigation of network shape and size is needed. To strengthen results, experiments with laser ceilometers rather than RBC's might be conducted--at more than the single test location, and with more test points than reflected in this report.

Camp, D. W., et al. "Fourth Annual Workshop on Meteorological Environmental Inputs to Aviation Systems, 25-27 March 1980, Tullahoma, Tenn." Bulletin of the American Meteorological Society, Vol. 61, No. 12, Dec., 1980.

Comments by the Fog, Visibility, and Ceilings Committee included questions regarding the requirements for SVR. A new definition for prevailing visibility was suggested, and the committee supported further progress toward automation.

Chisholm, D. A. and Jacobs, L. P. An Evaluation of Scattering Type Visibility Instruments. Air Force Cambridge Research Laboratories Report No. AFCRL-TR-75-0411, Instrumentation Paper No. 237, Bedford, Mass., July, 1975.

This interesting report presents complete evaluations of the EG&G Forward Scatter Meter, the Impulsphysik Videograph, and the MRI Fog Visiometer. The sensors were evaluated for potential use in remote and fully automated weather observation systems. The report indicated generally satisfactory performance of the sensors, with some specific limitations. Results agree with those found by other investigators--that the sensors generally work well in uniform visibility conditions but have problems in highly variable visibility situations. No solution is offered.

Chisholm, D. A. and Kruse, H. The Variability of Airfield Visibility: A Preliminary Assessment. Air Force Cambridge Research Laboratories Report No. AFCRL-74-0027, Environmental Research Paper No. 462, Bedford, Mass., Jan., 1974.

An interesting series of tests that were made to determine sensor representativeness during a variety of weather conditions. Conclusions paralleled those of other similar tests: for a complete description of runway visibility, several sensors are needed.

Coleman, H. S., Morris, F. J., and Rosenberger, H. E. "A Photo-Electric Method of Measuring the Atmospheric Attenuation of Brightness Contrast Along a Horizontal Path for the Visible Region of the Spectrum." Journal of the Optical Society of America, Vol. 39, No. 7, July, 1949.

An interesting early experiment designed to measure the attenuation of brightness contrast by the atmosphere. The authors concluded that the brightness contrast is exponentially attenuated and that the attenuation coefficient is insensitive to the naturally occurring local variations in illumination along the observation path.

Cwalinski, R., Lansinger, J. M., and Tank, W. G. Field Testing and Evaluation of Methods for Measuring Visibility. U.S. Environmental Protection Agency, Office of Research and Development, EPA-650/275-039, Washington, D.C., Apr., 1975.

Despite a few minor errors, this report is an important source of performance information on visibility sensors in limited use. The authors compared a telephotometer, a nephelometer, and a special folded-baseline laser transmissometer with routine local FAA visibility observations. The study appears to have been carefully performed, although the human observations seem to have been accepted without a more rigorous analysis of the subject. The authors recommend that the telephotometer be developed as a field sensor for visibility.

Czika, J. and Shreeve, K. H. Remote Monitoring of Visibility in Mountain Passes. Federal Aviation Administration, Report No. FAA-RD-74-53, Washington, D.C., Apr., 1974.

Good results were obtained from an experiment in which a slow-scan TV system viewed mountain pass weather conditions. Results were not as good, however, as those that would have been obtained if a human observer had been located at the remote site. While the method is promising, the equipment used does not appear adequate for estimating prevailing visibility.

de Boer, J. B. Visibility of Approach and Runway Lights. Philips Research Report No. 6, 1951.

An important early report dealing with an often neglected area--the physiological aspects of visibility.

Department of Transportation. Runway Visual Range Signal Data Converter System. Federal Aviation Administration Specification FAA-E-2267a, Washington, D.C., Aug. 1, 1969.

Department of Transportation. Transmissometer Set. Federal Aviation Administration Specification FAA-E-2404, Washington, D.C., Oct. 6, 1969.

Departments of Commerce, Defense, and Transportation. Federal Meteorological Handbook No. 1. 2nd ed., Washington, D.C., Jan. 1, 1979.

This publication walks the narrow path between strict standardization of weather observations and practical field utilization. Considering the difficult task it undertakes, it does a good job, but it leaves much material open to interpretation.

Departments of Transportation and Commerce. Aviation Weather, for Pilots and Flight Operations Personnel. Washington, D.C., revised 1975.

An excellent publication, particularly for those who want a practical grounding in meteorology.

Douglas, C. A. "The Development of the Runway Visual Range Concept and Its Operational Use." Meeting of the IES Aviation Committee, La Jolla, Calif., Oct., 1977.

Interesting review of the history of RVR, and a summary of RVR concepts.

Douglas, C. A. "Visibility in Aviation." Second Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems, University of Tennessee Space Institute, Tullahoma, Tenn., Mar., 1978.

Douglas, C. A. and Booker, R. L. Visual Range: Concepts, Instrumental Determination, and Aviation Applications. National Bureau of Standards Monograph 159, Washington, D.C., June, 1977.

> A contemporary classic, vital to anyone who is interested in either the history of visibility observations or current practices. This is an excellent source book for definitions, techniques, and activities in the field of visibility.

Douglas, C. A. and Young, L. L. Development of a Transmissometer for Determining Visual Range. Civil Aeronautics Administration Technical Development Report No. 47, Washington, D.C., Feb., 1945.

> This report chronicles the development of the transmissometer, a sensor completely relied upon in the United States and other nations for generating RVR, RVV, and other visibility descriptors. Of particular interest is the work that was done to calibrate the sensor; although ambitious, the number of test observers and calibration sites were quite limited.

Duntley, S. Q. "The Reduction of Apparent Contrast by the Atmosphere." Journal of the Optical Society of America, Vol. 38, No. 2, Feb., 1948.

> A largely theoretical treatment of the visibility contrast concept, with reference to Blackwell's work. Of particular interest is Duntley's view of an observer's visibility upward and a pilot's visibility downward in a "circle of visibility." Duntley relates his work to results obtained from the transmissometer, which was then newly developed.

Duntley, S. Q. "The Visibility of Distant Objects." Journal of the Optical Society of America, Vol. 38, No. 3, Mar., 1948.

> This paper identifies the principal factors involved in the visibility of an object, indicates how each factor affects the range of visibility, and supplies charts that combine these factors. These charts can be used to find the limiting range under any set of prevailing conditions. Much of the data used is Blackwell's. Duntley introduces a subject relatively new for that time period: visibility along inclined paths of sight.

Eggert, W. E. Approach Visibility Studies at Newark. Federal Aviation Agency, AMB Project D-1-902, Washington, D.C., Sept., 1960.

The first comprehensive program undertaken to develop slant visual range. In this case, the product was approach light contact height. The report analyzes 2,375 instrument approaches carried out during 23 months of evaluation at Newark Airport, Newark, N.J. Limitations were placed on the system by the totally ground-based measurements, which assumed relative uniformity of visibility conditions with height. There was also resistance to the system with respect to the probabilities of sighting runway lights. Users seemed to demand absolute values of light contact--an unlikely possibility.

Ettenheim, George P. Considerations in Visibility Monitoring Experiments. MRI, Inc., Altadena, Calif., Apr., 1979.

A short monograph directed toward visibility measurements in air pollution. Interesting description of observing procedure in the field.

Gavrilov, V. A. Visibility in the Atmosphere. U.S. Army Foreign Science and Technology Center, FSTC-HT-23-052-71, Leningrad, 1966.

A massive publication dealing with all aspects of visibility. In general, it summarizes the state of the art (at that time) of visibility measurements and observations. A good basic research publication, despite a rather fuzzy translation.

George, D. H. "Estimates of Fog Element Length." Journal of Applied Meteorology, Vol. 11, No. 5, Aug., 1972.

Haig, T. O. and Morton, W. C. III. An Operational System to Measure, Compute and Present Approach Visibility Information. Air Force Cambridge Research Center Report No. AFCRC-TN-58-417, Air Force Surveys in Geophysics No. 102, Bedford, Mass., June, 1958.

An important early attempt to develop a form of SVR. The report is quite comprehensive for its period. There were two functional problems with the system: (1) it was at least partially dependent on low-intensity threshold lights and (2) the recommended system was never tested.

Hess, Seymour L. Introduction to Theoretical Meteorology. Holt, Rinehart and Winston, New York, 1959.

Hochreiter, F. C. Analysis of Visibility Observation Methods. Environmental Science Services Administration, Technical Memorandum WBTM T & EL 9, Sterling, Va., Oct., 1969.

This report deals in a very practical manner with visibility sensors and human visibility observations. Sensor types and principles of operation are explained simply and clearly.

Standard visibility observations are discussed, and a summary of observation problems is provided. A particularly useful section, although a bit out of date, is an appendix that lists a considerable number of visibility sensors, along with their characteristics and prices. It would be interesting to see an updated version.

Huschke, Ralph E., ed. Glossary of Meteorology. American Meteorological Society, Boston, 1959.

This is a valuable compilation of meteorological definitions. It is also a bit dated, having been published in 1959. Although most definitions remain current, the book needs updating to reflect developments in the last two decades.

Ito, H. "Time and Space Variation in Meteorological Elements in the Aerodrome and Its Vicinity." Aeronautical Meteorology, World Meteorological Organization, Technical Note 95, Geneva, Oct., 1969.

Jones, R. F. "Time and Space Variations of Visibility and Low Cloud Within the Approach Control Area." Aeronautical Meteorology, World Meteorological Organization, Technical Note 95, Geneva, Oct., 1969.

Kaufman, J. E., ed. IES Lighting Handbook. 4th ed., Illuminating Engineering Society, New York, 1966.

Kotsch, William J. Weather for Mariners. Naval Institute Press, Annapolis, Md., 1977.

After being so closely involved with aviation weather, it is interesting to read a book dealing with an equally important weather specialty. Of particular interest is the section on the forewarning and formation of fog.

Lansinger, J. M. Instrumental Measurements of Visibility. Physical Dynamics Northwest, Inc., Report No. HAOS-04, Bellevue, Wash., Mar., 1978.

This report describes a field measurement program involving telephotometer and nephelometer measurements. The test method and sensor descriptions are interesting, but no summary of results is provided.

Larsson, A. J., Marut, J. K., and Northedge, R. L. Tables of Runway Visual Range Values as a Function of Transmittance and Various Values of Pilot's Illuminance Threshold and Light Targets. Federal Aviation Administration, Report No. FAA-RD-70-58, Washington, D.C., Aug., 1970.

Lefkowitz, M. Studies in the Field of Approach Visibility Measurements and Instrumentation. Federal Aviation Agency, final report, Project No. 202-2-1X, Atlantic City, N.J., Apr., 1962.

This study continued the experiments that were conducted at Newark Airport in the late 1950's. Results generally confirmed those obtained at Newark and were similarly limited by ground-based instrumentation, which could not fully measure parameters along the glide slope.

Lefkowitz, M. and Bradley, J. T. Relationship of Automated Weather Observations to Subjective Elements. American Society for Testing and Materials, Special Technical Publication 653, Philadelphia, Pa., 1979.

Lefkowitz, M. and Schlatter, E. E. An Analysis of Modifications to Runway Visual Range Equipment for Low RVR Values. U.S. Weather Bureau, SRDS Report No. RD-66-9, Atlantic City, N.J., Feb., 1966.

Several transmissometer configurations using 250-foot baseline systems were recommended. Only single systems were installed in the field for operational purposes.

Lefkowitz, M. and Schlatter, E. E. An Analysis of Runway Visual Range. U.S. Weather Bureau Report No. RD-66-100, prepared for the Federal Aviation Administration, Atlantic City, N.J., Dec., 1966.

This report contains three basic sections. The first is a straightforward explanation of the RVR concept. The second is a history of the development of RVR, taken from early records. The final section describes a benchmark experiment conducted to verify the RVR concept, perhaps the only such effort undertaken in the United States until 1966. For practical reasons as well as those of economy, stationary test observers were used in the disciplined field experiment. While results were significant, the application of stationary observers instead of pilots in cockpits must be considered a limiting factor.

Lillesaetter, O. "Parallel-Beam Attenuation of Light, Particularly by Falling Snow." Journal of Applied Meteorology, Vol. 4, Oct., 1965.

The author used an optical link to relate attenuation of light to the rate of falling snow. He theorizes that the measurement of attentuation by a short optical link would be a good way to measure rate of snowfall and visibility with excellent time resolution. This paper is interesting, particularly for its possible application to optical visibility sensors.

Lomer, L. R. Fog Detectors for Unmanned Aids to Navigation. U.S. Coast Guard Field Testing and Development Center, Report No. 512, Baltimore, Md., July, 1970.

From both performance and mechanical standpoints, this is one of the most carefully documented reports available regarding the Videograph. It includes extensive comparisons between the Videograph and the transmissometer, although there is no specific mention of human observers. Coast Guard interest in this sensor was for ranges above three miles.

Malm, W. "Considerations in the Measurement of Visibility." Journal of the Air Pollution Control Association, Vol. 29, No. 10, Oct., 1979, pp. 1042-1052.

A highly technical, comprehensive paper dealing with the problems of measuring visibility. It takes a somewhat negative view of current practices, but this could be regarded as rather realistic.

Mancuso, R. L. and Uthe, E. E. Computer Model for Investigating the Strategy of Automatically Estimating Prevailing Visibility. Stanford Research Institute, Menlo Park, Calif., Sept., 1972.

A computer modeling approach to the automation of visibility. The detailed report is interesting, but the method has not been very strongly pursued by other investigators. The authors indicate that without complete knowledge of real atmospheric conditions, neither the results nor applicability of their model can be certain.

McCartney, E. J. Optics of the Atmosphere. John Wiley & Sons, New York, 1976.

An interesting and up-to-date book dedicated to the scattering processes that occur in the atmosphere and the resulting effects on atmospheric propagation of light. Although the book includes much material that is not directly applicable, the sections on scattering, visibility, and characteristics of haze, fog, clouds, and rain are worth reading.

Middleton, W. E. Knowles. Vision Through the Atmosphere. University of Toronto Press, Toronto, reprinted 1963.

A classic. Absolutely required reading for everyone with a serious interest in visibility. A very detailed treatment of the subject. Complex at times, but no more so than the subject it covers.

Minnaert, M. The Nature of Light and Colour in the Open Air. Dover Publications, Inc., New York, 1954.

An interesting popular publication that is typified by the publicity blurb on its cover, "Why is falling snow sometimes black?" (We won't hold you in suspense; it's due to optical effects created when the eye uses the surrounding background as a contrast comparison.) In rather small bites, the book provides considerable information, at the lowest technical level, on subjects of interest to this report.

Morton, W. C. III and Haig, T. O. Variations of Atmospheric Transmissivity and Cloud Height at Newark. Air Force Cambridge Research Center Report No. AFCRC-TN-57-613, Air Force Surveys in Geophysics No. 91, Bedford, Mass., Jan., 1958.

An early study of visibility variability. Although the data were statistically analyzed, results were limited by the use of only two sites at a single geographical location.

Muench, H. S., Moroz, E. Y., and Jacobs, L. P. Development and Calibration of the Forward Scatter Meter. Air Force Cambridge Research Laboratories Report No. AFCRL-TR-74-0145, Instrumentation Paper No. 217, Bedford, Mass., Mar., 1974.

A definitive report on the forward scatter visibility sensor. The AFCRL had deployed 30 such instruments in a network of automatic weather stations. Although comparisons with the transmissometer produced relatively low agreement ($\pm$19 percent), agreement with human observers exceeded $\pm$34 percent. The authors reviewed problems that arise when using comparisons with human observations and estimated the accuracies of visual range systems at airports.

National Weather Service. Analysis of a Backscatter Visibility Measuring Technique. Test and Evaluation Laboratory Report No. 3-71, Sterling, Va., Aug., 1971.

Some of the National Weather Service's earliest experiences with the Videograph. The sensor was compared with the transmissometer at the Test and Evaluation Division at Sterling, Va. Results were favorable for ease of installation, reliability, and calibration stability. It was because of this report that the Videograph received further testing as a candidate sensor for visibility automation.

National Weather Service. Automation of Cloud and Visibility Observations: Single Sensor Methods. Test and Evaluation Report No. 3-76, Sterling, Va., Nov., 1976.

An important report that analyzes results of AUTOB, the first of the current generation of totally automatic weather stations developed by NWS. Both automated cloud and visibility methods that are based on a single sensor are discussed. Results are generally good, but a larger geographical sample using dedicated observers as test standards might have been more desirable.

National Weather Service. Automation of Visibility Observations: Design Algorithms. Test and Evaluation Division Report No. 5-80, Sterling, Va., July, 1980.

These algorithms updated the original AV-AWOS algorithms published in November, 1978. Although the algorithms are a result of the earlier development/testing program, there is no indication that they have been independently tested.

National Weather Service. Discussion of Sensor Equivalent Visibility. National Oceanic and Atmospheric Administration, Technical Memorandum WBTM T & EL 11, Sterling, Va., July, 1971.

Sensor equivalent visibility (SEV) is any equivalent of human visibility that is derived from instrumental measurements. The report discusses conversion from sensor measurements to SEV. Of particular value is the section on limitations of SEV, including an excellent review of representativeness. There are also comparisons of prevailing visibility with several potential automation strategies.

National Weather Service. (REREX) Remote Readout Experiment for Clouds and Visibility. National Oceanic and Atmospheric Administration, Technical Memorandum NWS T & EL 14, Sterling, Va., Dec., 1973.

National Weather Service. User's Guide to the Automatic Observing Station (AUTOB). Silver Spring, Md., Jan., 1979.

National Weather Service. Videograph Calibration. Test and Evaluation Laboratory Report No. 4-73, Sterling, Va., July, 1973.

This report describes the basic calibration of the Videograph. After electronic and mechanical testing, the sensors were compared with carefully filtered human observations at five locations throughout the contiguous states and Alaska. To fully describe the atmosphere, it was found that separate calibrations would be needed for fog/haze, rain, snow, day, and night. It was proposed that the basic calibrations be limited to those for fog/haze, day, and night.

Neuberger, H. Introduction to Physical Meteorology. Pennsylvania State University, University Park, Pa., 1957.

An excellent textbook for concise and straightforward discussions of topics vital to visibility. The book reflects the author's course material as far back as May, 1951, so some of the content is a bit dated now. But the discussions of condensation processes, visibility, and meteorological optics are worth referring to.

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O'Brien, H. W. "Visibility and Light Attenuation in Falling Snow." Journal of Applied Meteorology, Vol. 9, Aug., 1970.

The author undertook a study to establish empirical relationships that would improve understanding of the attenuation of light by falling snow. A very practical and interesting paper, even though the experimenters were hampered by equipment failures.

Oddie, G. J. "Runway Visual Range." ICAO Bulletin, Apr., 1970.

A rather critical look at the RVR concept. The author points out some problems with the system and discusses future prospects.

Olbers, W. "Relationships Between Measurements of Standard Visual Range and Runway Visual Range." Annalen det Meteorologie, No. 3, 1967.

Olbers reviews several early tests of RVR and offers some reasons for differing estimates of RVR by observers and pilots. Most of these explanations are related to the observer and pilot having different axes of illumination with respect to the light target.

Penndorf, R., Goldberg, B., and Lufkin, D. Slant Visibility. Air Force Cambridge Research Center, Air Force Surveys in Geophysics No. 21, Dec., 1952.

A survey of slant visibility problems. Excellent background material. Considers in detail the effects of the position of the sun in the sky.

Pritchard, B. S. and Elliot, W. G. "Two Instruments for Atmospheric Optics Measurements." Journal of the Optical Society of America, Vol. 50, No. 3, Mar., 1960.

This article discusses the design and construction of two instruments for determining optical properties of the atmosphere--a recording nephelometer and a portable transmissometer.

Riissanen, J. and Lumme, T. On the Measurement of RVR at Helsinki Airport. Finnish Meteorological Institute Contributions No. 73, Helsinki, 1969.

This paper reports the results of experimentation with automatic measurement of RVR in Finland, which largely paralleled U.S. tests. The Finns found such systems to be feasible, emphasizing the need for good maintenance of runway lights and transmissometers.

Rozenberg, G. V. Twilight. Plenum Press, New York, 1966.

This is a comprehensive study of atmospheric optics during twilight. For reasons of convenience or economy, twilight plays a very small role in both human and automated observations of visibility. This book, probably directed more toward the theoretician, might increase interest in the consideration of visibility during twilight.

Schlatter, E. E. and Lefkowitz, M. Evaluation of Multi Transmissometer Systems. Environmental Science Services Administration, SRDS Report No. RD-68-49, Atlantic City, N.J., Aug., 1968.

An ambitious and well-documented test program designed to evaluate multi-transmissometer systems along a runway. A big "plus" for this report is that data were obtained from five airfields across the United States rather than from just one test site.

Sheppard, B. E. Calibration of Scattering-Function Visibility Sensors at Toronto International Airport March 1973 to December 1975. Canada Atmospheric Environment Service Report TR 4, Toronto, Dec., 1978.

An important report, describing the ambitious "multi-visibility recording system" for establishing a data bank of visibility-related parameters. These would be used to assess measurement techniques and specific instruments for application in automated meteorological stations.

Sheppard, B. E. and Clink, W. L. The Videograph Calibration Experiment at Toronto International Airport 23 November 1970 to 31 October 1971. Canada Atmospheric Environment Service Report TR 1, Toronto, Feb., 1974.

This is the technical record of the Canadian calibration of the Videograph against human visibility observations. The authors' data reduction technique involved drawing best-fit curves by visual estimate through scatter diagrams. They found that the Videograph deviated from human observations depending on weather, but no analysis was performed of the human observations.

Sheppard, B. E. and Clink, W. L. Visibility Through Various Obscuring Media as Determined by the Videograph. Canada Atmospheric Environment Service Report TEC 813, Toronto, Jan., 1975.

This report deals with the authors' preliminary Videograph calibration. It appears to be a condensed version of Report TR 1.

Sperry Gyroscope Co. A Flight Investigation of the Performance of Low Ceiling/Visibility Meteorological Equipment. Report No. 5245-4059, prepared for the Air Navigation Development Board, Great Neck, N.Y., Dec., 1954.

Sperry participated in some early attempts to develop a slant visual range technique. This well-written report chronicles a careful, detailed experimental approach to the problem. Particular emphasis is placed on the use of aircraft and pilots in the observation phase. It would be interesting to see these results verified with updated equipment.

Stewart, H. S., Drummeter, L. F., and Pearson, C. A. The Measurement of Slant Visibility. U.S. Naval Research Laboratory, Report N-3484, Washington, D.C., June, 1949.

Some very early concepts regarding the measurement of SVR from the ground.

Twomey, S. and Howell, H. B. "The Relative Merit of White and Monochromatic Light for the Determination of Backscattering Measurements." Applied Optics, Vol. 4, No. 4, Apr., 1965.

This paper concludes that monochromatic sources of light are inferior to white light for back scatter measurements. The authors also believe that the aerosol climatology or local scattering-extinction relationship should be carefully studied at any location where the use of a single-ended visibility sensor is being considered.

U.S. Weather Bureau. Final Approach Visibility Studies: Final Report. Prepared for the Air Navigation Development Board, Washington D.C., Apr., 1955.

A summary of several interim reports dealing with the development and conceptual basis of the transmissometer, RVR, SVR, ceilometer, and remote TV applications. Although some methods are a bit dated now, the report is important reading for professionals in this field.

U.S. Weather Bureau. Final Approach Visibility Studies: Fiscal Year 1952 Progress Report. Prepared for the Air Navigation Development Board, Washington, D.C., Mar., 1953.

This is one of a series of reports issued during the early days of RVR and SVR development. It is essential reading for those wishing to learn details of the initial testing of the transmissometer and rotating-beam ceilometer. The investigators proposed many tentative conclusions that today have been accepted as fact.

U.S. Weather Bureau. Final Approach Visibility Studies: Fiscal Year 1952 Progress Report, Part III. Washington, D.C., Jan., 1954.

A well-conceived remote visibility experiment using up-to-date (for that period) TV equipment. Unfortunately, tests were marred by insufficient low-visibility periods.

Viezee, W., Oblanas, J., and Collis, R. T. H. Evaluation of the Lidar Technique of Determining Slant Range Visibility for Aircraft Landing Operations. Air Force Cambridge Research Laboratories Report No. AFCRL-TR-73-0708, Bedford, Mass., Nov., 1973.

Considerable theoretical and pragmatic groundwork on SVR is reflected by this report. Practical experiments, however, were limited to three periods of dense fog.

Vogt, H. "Visibility Measurement Using Backscattered Light." Journal of the Atmospheric Sciences, Vol. 25, Sept., 1968.

A useful parallel to the NWS Videograph calibrations. Vogt's tests showed that back scatter sensors indicate visibility as well as other types of sensors, with an accuracy of about 20 percent if no completely abnormal distribution of aerosol particles is present. Vogt's recommendations include a suggestion that calibrations be made separately, depending on aerosol type.

APPENDIX C

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