DEPARTMENT OF COMMERCE ★ NATIONAL BUREAU OF STANDARDS

NBS MONOGRAPH 159

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Visual Range:

Concepts, Instrumental Determination, and Aviation Applications

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Visual Range:

Concepts, Instrumental Determination, and Aviation Applications

t. Monograph no. 159

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Sponsored by:

Federal Aviation Administration
Systems Research and Development Service
Weather Data Section
Washington, D.C. 20553

U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary

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Issued June 1977

Library of Congress Cataloging in Publication Data

Douglas, C A

Visual range.

(National Bureau of Standards monograph ; 159)

Bibliography: p.

Supt. of Docs. no.: C13.44:159

1. Airports--visibility. 2. Transmissometer. 3. Ceilometer.
I. Booker, R. L., joint author. II. Title. III. Series: United States.
National Bureau of Standards. Monograph ; 159.
QC100.U556 no. 159 [TL557.V5] 602'.1s [629.135'2] 77-7343

National Bureau of Standards Monograph 159

Nat. Bur. Stand. (U.S.), Monogr. 159, 362 pages (June 1977)
CODEN: NBSMA6

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1977

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $5.00

Stock No. 003-003-01782-5

☆ U.S. GOVERNMENT PRINTING OFFICE : 1977 O—240-848

ABSTRACT

This document is a review of the principles, procedures, and instruments used in the measurement of visual range. The fundamental concepts of the visual range of objects and lights are discussed. The principles of operation of the several classes of atmospheric attenuation meters are reviewed and representative instruments are described. The course of development of the NBS transmissometer, its validation and application to aviation operations is reported. An error analysis is made of the effects of instrument errors and of differences in observer thresholds on visibility measurements. A chronological review of the development and application of the runway visual range concept is included together with a discussion of cloud height measurements.

KEY WORDS: Ceilometer, runway visual range, scattering, transmissometer, visibility, visual range.

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1. INTRODUCTION

The Federal Aviation Administration of the Department of Transportation requested that the National Bureau of Standards, by InterAgency Agreement No. DOT-FA72WAI-267, "provide analysis, experimentation, and report preparation work in the areas of ceiling, visibility, and related techniques and instrumentation." The study was to culminate in the preparation of "an encyclopedia of principles, procedures, and equipments utilized in the measurement of visual range in the United States". This report was prepared in an effort to fulfill the stated requirement.

The development and application of the visual range concept in the United States is not well documented. Very little work was reported in the formal literature. Intergovernmental reports were not given wide circulation and at this time are not usually available. Often decisions were made at meetings of ad hoc committees, by memoranda, or by letters. In preparing this report we have reviewed the formal literature (restricting our efforts almost entirely to papers in English) and the collection of reports, progress reports, memoranda, correspondence, information copies, etc. which has collected during some 35 years of work on problems of visual range as applied to aviation. In our preparation of the text we have referenced formal papers and reports as applicable, but we have not referenced correspondence, memoranda and the like. There have been a few instances in which we could find no documentation relating to a significant step. In those instances we have relied on the memory of the senior author.

At the risk of being slightly repetitive, we have, in so far as practicable, made each chapter substantially independent of the others. In Chapter 2 we define and explain the photometric, meteorological, and aeronautical terms used in the report. Chapter 3 is a chronological resume of the development and application of the runway visual range concept, presented without a detailed technical analysis in order to maintain a historical perspective. Chapters 4 and 5 are detailed discussions of the theory of the visual range of objects and lights and of instruments used to measure atmospheric clarity, respectively.

Chapters 6 and 7 comprise a review of the work of NBS and other related work in the development of the transmissometer, gathering together reports of work which has been previously presented in progress reports to sponsors, working and discussion papers, and internal reports. Chapter 8 is a review of the development of the ceilometer and of studies in the measurement of cloud height. The report closes with a bibliography of the books, papers and reports consulted during its preparation and found to be pertinent.

The scope of this report does not include a discussion of the parallel paths of development of visual range meters in other countries or the application of the NBS transmissometer to other purposes such as air pollution, fog dispersal and camouflage studies. Nor does it include an evaluation of the effectiveness of approach and runway lights; only the visual range of these lights is considered.

In preparing this report, extensive use has been made of extracts from early National Bureau of Standards, Civil Aeronautics Administration, and Weather Bureau reports.

English photometric units and units of length have been used in most of this report, since the original choices for values of such items as distances and illuminance were rounded values when expressed in English units. Where the original work was in metric units, as in the work of the International Civil Aviation Organization, metric units have been retained. Parenthetical equivalents are given only when considered essential since it is expected that most readers will be "bilingual". However, because of the complexity of photometric units, tables of equivalents are given in Sections 2.1.6 and 2.1.9.

At this point we want to pay tribute to the many persons who contributed significantly to the development and application of the RVR concept in the United States. At the risk of omitting some deserving persons, we express our appreciation to our former colleagues at NBS: to F. C. Breckenridge,

who with H. J. C. Pearson of the CAA, initiated the ceilometer and transmissometer development; to M. K. Laufer and L. L. Young who designed the initial model of the transmissometer; to A. N. Hill for his assistance in the design and testing of the first commercial transmissometers; to J. W. Simeroth, who for twenty years was in charge of the NBS Visual Landing Aids Field Laboratory at Arcata, and to his associates, especially J. E. Davis and J. C. Wilkerson; to D. H. Hutchison and G. H. Stocker, Meteorologists at the Landing Aids Experiment Station 1946-1950; to R. E. Crossley of the Crouse Hinds Company, for his mechanical design of the commercial transmissometer; to our associates L. W. Foskett, R. H. Guenthner, Joseph N. Cooper, and Dale Harris, of the Weather Bureau, who implemented the operation of the civil runway range systems; to J. W. Connolly, who when with the Air Force, conducted the operational suitability test of the transmissometer; to E. F. Corwin, A. L. Lewis, R. D. Hartz of the Navy for their continued support of visibility studies at NBS; to W. E. Eggert, E. W. Estelle, C. G. Knutson, Mathew Lefkowitz, and E. E. Schlatter of the Weather Bureau, who conducted the flight tests at Newark and Atlantic City; and to the many people of the CAA and FAA for technical and administrative support during the "testing" period, especially to B. J. Vincent. To those whose names we have omitted, we apologize and express our sincere appreciation of their contributions.

2. DEFINITIONS OF TERMS

This section contains the definitions and, where required, the explanations of technical terms as used in this report. Definitions are based upon current usage, and, when there has been a change in usage, an explanation is given.

The following publications have been used in the preparation of these definitions:

ASTM Special Technical Publication 475, Nomenclature and Definitions Applicable to Radiometric and Photometric Properties of Matter. [6]*

CIE International Lighting Vocabulary. [71]

Federal Meteorological Handbook No. 1. Surface Observations Circular N [36]

Holmes, Terminology for Flashing Light Signals. [46]

IES Lighting Handbook [51]

International Civil Aviation Annex 14 [53, 54]

International Dictionary of Aids to Marine Navigation, Chapter 2, Visual Aids. [52]

Middleton, Vision Through the Atmosphere. [95]

USA Standard Z7.1-1967, Nomenclature and Definitions for Illuminating Engineering. [5]

World Meteorological Organization Guide, Chapter 10. [128]

In this section the terms are arranged so that, insofar as possible, technical terms used in a definition have been defined before they are used in defining other terms. As an aid in locating specific terms an alphabetical index of terms is given at the end of this Chapter.

For clarity, some of the definitions are in colloquial language rather than in the precise general terminology of the publications referenced above.

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*Numbers in brackets refer to references listed at the end of the report.

2.1 GENERAL PHOTOMETRIC TERMS

The symbols used in these definitions, and throughout the report, are consistent with those recommended by the International Commission on Illumination.

2.1.1 Light:-

For the purpose of this report **light** may be considered as visually evaluated radiant energy. Strictly speaking the term **light** should be applied only to that part of the electromagnetic radiation spectrum which is capable of causing a visual sensation directly. However, it is common engineering practice to apply the term to radiation which contains some ultraviolet and infrared radiation in addition to the visible radiation which is of primary concern; for example, "the light from a source incident on a photoelectric receiver".

The term **light** is also to mean the fitting or fixture which emits a light signal; for example, approach light.

2.1.2 Radiant Flux (Flux):-

The time rate of flow of radiant energy

Symbol: ϕ* unit: watt

2.1.3 Luminous Flux:-

The time rate of flow of luminous energy (light).

Symbol: ϕ* unit: lumen

When the context is clear the term **flux** is often used instead of **luminous flux.**

Unless otherwise indicated the luminous flux in question relates to photopic (cone) vision.

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*The symbols for photometric quantities are the same as those for the corresponding radiometric quantities. When it is necessary to differentiate them the subscripts v and e should be used, e.g., ϕ_v and ϕ_e.

2.1.4 Luminous Intensity (Intensity):-

The luminous flux per unit solid angle.

Symbol: I unit: candela

older units: candle,
candlepower.

For engineering purposes the terms candela, candle and candlepower can be considered synonomous.

The defining equation of luminous intensity is
$I = d\phi/d\Omega$.

The intensity of a source is a function of the direction in which the light is emitted. Thus the direction of emission with respect to a known frame of reference should be stated. The luminous intensity is the luminous flux on a small surface normal to that direction, divided by the solid angle (Ω) (in steradians) that the surface subtends at the source. Light fittings are frequently described in terms of their peak intensity or by their average intensity.

2.1.5 Average Intensity (Representative Intensity):-

The concept of using an average or representative intensity in computing the effective visual range of airfield lights originated in the U.S. during the early development of the runway visual range program. See Sections 3.9.1 and 3.11.3.3, and reference [40].

During its Fifth Meeting, the Visual Aids Panel stated that the intensity to be used in the assessment of RVR should be the intensity of a typical new light averaged over the specified beam spreads, with all intensities greater than three times the minimum intensity within the specified region being considered as three times the minimum, multiplied by an appropriate reduction factor [67]. The beam pattern is described as an ellipse with the lengths of its axes equal to the specified vertical and horizontal beam spreads. (A Cartesian system with vertical and horizontal angles as the coordinates is assumed).

If detailed iso-candela curves, or numerous intensity distribution curves are available, the average intensity within the ellipse is computed from these curves. Frequently, detailed information is not available. In such cases an approximation to the average intensity is computed from the horizontal and vertical intensity distributions through the beam axis. (The beam axis is defined as lying midway between the 50% points of these two distributions.) The approximate average intensity is taken as the average of the average intensity in the horizontal plane between the specified horizontal angles and the average intensity in the vertical plane between the specified vertical angles.

In all cases, the restriction that any intensity more than three times the minimum be treated as being three times the minimum must be observed. This restriction is needed to avoid the undue influence on the "average" intensity which would be produced by a narrow peak having an intensity much greater than the intensity in other parts of the specified region.

2.1.6 Illuminance (Illumination):-

Luminous flux per unit area.

Symbol: E   Unit: SI - lux (one lumen per square meter).
English - footcandle (one lumen per square foot.)

The defining equation is

$$E = d\phi/dA.$$

Note: The term **illumination** is frequently used instead of the preferred term **illuminance** although this usage conflicts with the recommended practice. In present usage the ending **tion** is reserved for terms designating processes; that is, the process of reflection, transmission, illumination, etc. The ending **ance** is used for the designating of measurable quantities.

Other units of **illuminance** which have been used in relation to vision through the atmosphere are

mile candle:- (one lumen per square mile) and kilometer candle (one lumen per square kilometer).

A **mile candle** is the **illuminance** which would be produced by a source having an intensity of one candela at a distance of one mile in a perfectly transmitting atmosphere. The terms footcandle, meter candle, mile candle, and sea mile candle are similarly defined with the unit of distance being changed as appropriate.

The **illuminance** produced on a surface a distance $\underline{x}$ from a point source and perpendicular to the line of sight in a perfectly clear atmosphere is given by the equation

$$E = I/x^2 \qquad (2.01)$$

where I is the intensity in <u>the direction of the line of sight</u>.

Relations between the several units of **illuminance** computed from this relation are given in table 2.1.

Table 2.1

Relations between Units of Illuminance

One lux = 10^6 kilometer candles = 2.59×10^6 mile candles*

= 0.0929 footcandles.

One footcandle = 10.76 lux = 1.076×10^7 kilometer candles

= 2.79×10^7 mile candles*.

One mile candle* = 3.59×10^{-8} footcandles = 0.386 kilometer candle

= 3.86×10^{-7} lux.

One kilometer candle = 10^{-6} lux (one microlux)

= 2.59 mile candles* = 9.29×10^{-8} footcandles.

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*When English units are used the usual practice is to use the term **mile candle** when the unit of length is a statute mile and **sea-mile candle** when the unit of length is a nautical mile. One mile candle is equal to 1.326 sea-mile candles.

2.1.7 Normal Illuminance:-

The **illuminance** measured at a point in a plane perpendicular to the incident rays.

In signal lighting the modifier **normal** is usually omitted. **Normal illuminance** is referred to as **illuminance.**

2.1.8 Point Brilliance:-

The normal illuminance produced by a (distant) source on a plane at the observer's eye. It is the quantity involved in the visual observation of a source of light when viewed directly from such a distance that the apparent diameter is not appreciable. The **point brilliance** is measured by the illuminance produced by the source on a plane at the observer's eye normal to the direction of the source.

Symbol: E_n SI Unit: lux (lx). Frequently expressed in microlux (μlx).
Non-metric Unit: Footcandle
Customary Units: Mile candle, sea-mile candle, kilometer candle.

2.1.9 Luminance:-

This is the most difficult concept to define. For purposes of this report the term can be best defined by a figure illustrating photometric concepts. Such an illustration, prepared by L. E. Barbrow of the National Bureau of Standards, is shown as figure 2.1. The following definition is that given in reference [5].

> "**Luminance** (Photometric Brightness),
> $L = d^2\phi/dw\,(dA \cos\theta) = dI/(dA \cos\theta)$.
>
> **Luminance** (photometric brightness) in a direction, at a point of the surface of a source, of a receiver, or of any other real or virtual surface is the quotient of the luminous flux leaving, passing through, or arriving at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing

The *<u>CANDELA</u> is the luminous intensity of 1/60 of 1 cm^2 of projected area of a blackbody radiator operating at the temperature of solidification of platinum, 2042 K

The *<u>LUMEN</u> is the luminous flux from 1 candela in all directions thru a unit solid angle of one steradian.

Point A to any B is 1 cm
BBBB is 1 cm^2

Point A to any C is 1 ft
CCCC is 1 ft^2

Point A to any D is 1 meter
DDDD is 1 m^2

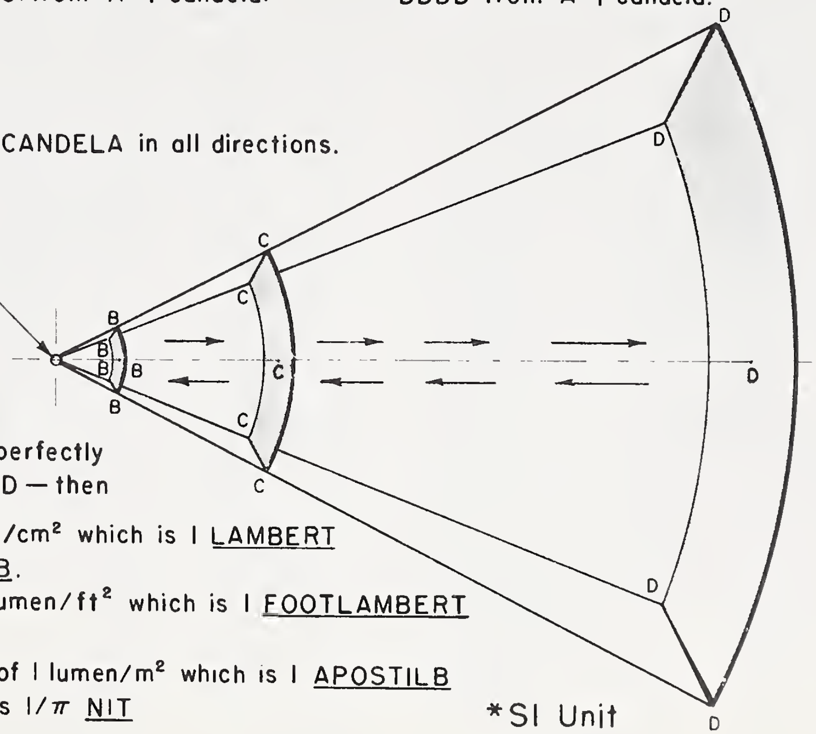
UNITS OF ILLUMINATION ⟶

The <u>PHOT</u> is the unit of illumination resulting from the flux of 1 lumen falling on BBBB from A-1 candela.

The <u>FOOTCANDLE</u> is the unit of illumination resulting from the flux of 1 lumen falling on CCCC. from A–1 candela.

The *<u>LUX</u> is the unit of illumination resulting from the flux of 1 lumen falling on DDDD from A–1 candela.

A = 1 CANDELA in all directions.



⟵ UNITS OF LUMINANCE

Assume 100% of the luminous flux from A (1 candela in all directions) is reflected in a perfectly diffuse manner by BBBB — CCCC — or — DDDD — then

BBBB will have a luminance of 1 lumen/cm^2 which is 1 <u>LAMBERT</u> or $1/\pi$ candela/cm^2 which is $1/\pi$ <u>STILB</u>.

CCCC will have a luminance of 1 lumen/ft^2 which is 1 <u>FOOTLAMBERT</u> or $1/\pi$ candela/ft^2

DDDD will have a luminance of 1 lumen/m^2 which is 1 <u>APOSTILB</u> or $1/\pi$ *candela/m^2 which is $1/\pi$ <u>NIT</u>

*SI Unit

Figure 2.1 Units of luminous intensity, luminous flux, illumination, and luminance.

the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction; or it is the luminous intensity of any surface in a given direction per unit of projected area of the surface as viewed from that direction."

In many of the earlier papers the term **brightness**, with the symbol B, is used instead of **luminance**.

Units of Luminance:

The endorsed method of expressing **luminance** is candelas per unit area, the defining equation being

$$L = I/A.$$

The SI unit of luminance is one candela per square meter. The **luminance** of lamp filaments has usually been expressed in candelas per square millimeter, or per square centimeter. In the English system both the inch and the foot have been used as the unit of length.

There is also a group of units contrived for the sake of numerical convenience, the lambert, or millilambert, in metric units and the footlambert in English units. The luminance of a uniform, perfect diffuser is one footlambert when the illuminance on it is one lumen per square foot (one footcandle).

Relations between several of the units of **luminance** in common use are given in table 2.2.

Table 2.2

Relations between Units of Luminance

One lambert = 10^3 millilamberts = 3.183×10^3 candelas per square meter = 9.290×10^2 footlamberts = 2.957×10^2 candelas per square foot.

One candela per square foot = 3.382×10^{-3} lamberts = 3.382 millilamberts = 10.76 candelas per square meter = 3.142 footlamberts.

One footlambert = 0.3183 candelas per square foot = 1.076×10^{-3} lamberts = 1.076 millilamberts = 3.426 candelas per square meter.

One candela per square meter = 0.2919 footlamberts = 9.290×10^{-2} candelas per square foot = 3.142×10^{-4} lamberts = 0.3142 millilamberts.

One millilambert = 3.183 candelas per square meter = 0.9290 footlamberts = 0.2957 candelas per square foot = 10^{-3} lamberts.

2.1.10 Brightness, Subjective Brightness, or Luminosity:-

These terms are used to describe the visual sensation. In practice, luminance is the descriptive term used for light energy effective at the eye. It is the physical stimulus. The **brightness** of a surface depends on various elements of the visual image as perceived by the eye and the brain. It is the sensation.

2.1.11 Contrast:-

As used in this report, **contrast** is defined by the following equation:

$$C = (L_o - L_b)/L_b \qquad (2.02)$$

where

L_o is the luminance of the object, and

L_b is the luminance of the background

The luminances referred to above are the **inherent** luminances; that is, the luminances as measured from a position, on the line of sight, sufficiently close to the object so that the measurements are not affected by atmospheric losses.

When an object is darker than its background, L_o is less than L_b and C is negative.

The inherent luminance of a truly black object is zero. Hence, for such an object, L_o is zero and the **contrast** is -1* for all backgrounds. This is the lowest **contrast** an object may have. Theoretically, there is no limit to the **contrast** for an object which is lighter than

---

*See 2.3.6

its background. However, under natural conditions, the maximum **contrast** which a sun-lighted white object may have is about 5 for a sky background and 20 for a terrestrial background.

2.1.2 Apparent Contrast:-

The **apparent contrast**, C_x, of an object at a distance, x, from the object is defined by the following equation:

$$C_x = (L_x - L_{bx})/L_{bx} \tag{2.03}$$

where L_x and L_{bx} are the apparent luminances of the object and its background respectively. These luminances are the luminances measured from the distance x.

Additional Material: For a more detailed explanation of photometric concepts see references [95], [51] and [5].

2.2.1 Transmission:-

Transmission is now defined as the passage of radiation through a medium without changes in the frequency of the monochromatic omponents of which the radiation is composed. In the past the term **transmission** has been used synonomously with transmittance. See the Note following definition 2.1.6.

2.2.2 Transmittance:-

The ratio of the transmitted radiant or luminous flux to the incident flux. That is

$$t = \phi/\phi_i . \tag{2.04}$$

Transmittance may be considered as the ratio of the flux from a source received incident on a receptor (which may be the eye) after passage through a medium, without refraction, to that which would be received if the medium were removed. Since the aerosols of the atmosphere both scatter and absorb light, the transmittance is **mixed**, that is, part of the flux from the source incident on the receptor has been transmitted from the source without scattering, and some after having been scattered in the direction of the receptor.

Thus

$$t = t_r + t_d \tag{2.05}$$

where

t is the (total) **transmittance**,

t_r is the regular **transmittance**, the **transmittance** based upon unscattered flux, and

t_d is the diffuse **transmittance**, the **transmittance** based upon scattered flux.

Note: The symbol τ is the internationally recommended symbol for transmittance. This symbol has not been used in this report since so many of the earlier reports and papers used $\underline{t}$.

The distance one can see is a function of the regular **transmittance.** In most of the literature pertaining to visual range, as in this report, the term **transmittance** is used without a modifier when **regular transmittance** is meant. The definition of **transmittance** given by WMO, "the fraction of luminous flux which remains in the beam after traversing an optical path of a given length in the atmosphere" implies **regular transmittance.**

Although **transmittance** is dimensionless, when the term **transmittance** is used to describe a state of the atmosphere the distance to which the **transmittance** applies must be stated, e.g., the **transmittance** over a baseline of 500 feet is 0.01.

Note: If the (regular) transmittance, t_b, of a uniform atmosphere over a path of length $\underline{b}$ is known, the (regular) transmittance, t_a, over a path of length $\underline{a}$ is given by the relation

$$t_a = (t_b)^{a/b} \qquad (2.06)$$

Equation (2.06) is valid only when the transmittance is independent of the wavelength(s) of the incident flux.

2.2.3 Transmissivity:-

Transmittance for unit distance within a light transmitting medium.

Symbol: T

The unit of length must be stated although the term is dimensionless.

Note: In current practice the endings **-tion** and **-sion** are used for the designation of processes, as in, **transmission**; the endings **-ance** and **-ancy** are used in reference to measurable quantities such as **transmittance**; and the ending **-ity** to the properties of materials or media. The term coefficient also refers to properties of materials or media.

The relation between the transmissivity, T, and the transmittance over a path of a given length, b, may be found from equation (2.06) by setting a equal to one. Since t_a is then the transmissivity, T,

$$T = (t_b)^{1/b} \tag{2.07}$$

or

$$t_b = T^b. \tag{2.08}$$

Equation (2.08) has caused difficulty to many who use dimensional analysis because the exponent of T does not appear to be dimensionless. It should be remembered that the exponent is in reality the ratio of two lengths, where the magnitude of the length in the denominator of the exponent is unity.

Equations (2.06), (2.07) and (2.08) and those following apply strictly only to monochromatic light or to an atmosphere which transmits light of all wavelengths equally. They are, however, sufficiently accurate in approximations for most work in atmospheric optics. See Section 6.4.3.

2.2.4 Transmissometer, Atmospheric:-

An instrument for measuring the regular transmittance of the atmosphere between two points in space. The term is usually used without the modifier atmospheric.

It is not possible to construct an instrument which will accept only the regularly transmitted light. The instrument will always accept some radiation which, though emitted by the source, would not be accepted by the receiver, had its durection not been changed by scattering enroute. In a well designed transmissometer the amount of scattered radiation accepted is kept as low as is feasible.

2.2.5 Absorption Coefficient, Atmospheric:-

The absorption coefficient, α, may be defined by the equation

$$\alpha = -d\phi_a/\phi dx$$

where

$d\phi$ is the flux absorbed as light passes through a lamina of thickness dx perpendicular to the line of sight and ϕ is the flux entering the lamina. The unit of length, must be stated.

The negative sign indicates that an increase in x is accompanied by a decrease in ϕ, that is, $d\phi$ and dx are of opposite signs, and α is, therefore, positive.

Note: The absorption coefficient is negligible in clean fog.

2.2.6 Scattering Coefficient, Atmospheric:-

The defining equation for the scattering coefficient, β, is

$$\beta = -d\phi_s/\phi dx$$

where $d\phi_s$ is the flux scattered as light passes through a lamina of thickness dx and ϕ is the flux entering the lamina. The unit of length must be stated.

2.2.7 Extinction Coefficient:-

The extinction coefficient, σ, is defined by

$$\sigma = -d\phi/\phi dx \qquad (2.09)$$

where $d\phi$ is the flux absorbed and scattered as light passes through a lamina of thickness dx and ϕ is the incident flux. It is apparent that

$$\sigma = \alpha + \beta \qquad (2.10)$$

The unit of legnth must be stated as σ per meter or σ per foot, etc.

Integration of equation (2.09) and applying the boundary condition that when x is equal to zero, ϕ is equal to ϕ_i, the incident flux yields the following equation for ϕ_x, the flux in the beam at a distance x:

$$\phi_x/\phi_i = e^{-\sigma x} \qquad (2.11)$$

Equation (2.11) is strictly applicable only to monochromatic light or to a non-selective atmosphere. See Section 6.4.3.

The quantity ϕ_x/ϕ_i is the transmittance over the distance x.

Hence

$$t_x = e^{-\sigma x} \qquad (2.12)$$

and since from (2.07)

$$T = t_x^{\ 1/x},$$

or

$$T = e^{-\sigma} \qquad (2.13)$$

$$\sigma = -\ln T. \qquad (2.14)$$

Note that the integration as performed is valid only if the atmosphere is spatially uniform and is not spectrally selective.

2.2.8 Scattering Coefficient Meter:-

An instrument for determining the scattering coefficient by measurements of the flux scattered from a light beam.

These meters are frequently called **extinction coefficient meters.** Since their response is not significantly affected by atmospheric absorption, their output is a function only of the scattering coefficient, β, not of the extinction coefficient, σ.

2.3 TERMS RELATED TO VISION

2.3.1 Threshold:-

The value of a physical stimulus (such as size, luminance, contrast or time) that permits an object to be seen a specific percentage of the time or at a specific accuracy level. Often **thresholds** are presented in terms of 50 percent, or 95 or 99 per cent, detection. However, the **threshold** also is expressed as the value of the physical variable that permits the object to be just barely seen. The **threshold** may be determined by merely detecting the presence of an object or it may be determined by discriminating certain details of the object, designated as detection and recognition thresholds respectively. Detection **thresholds** are applicable to laboratory, but usually not to practical, problems. See definition 2.3.4.

2.3.2 Illuminance Threshold (Visual Threshold, Threshold Illuminance):-

The minimum illuminance at the eye required to make a light source visible. This 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, and the criteria used in determining whether the light is "visible". Usually it is not greatly affected by the color of the light. See Section 4.4.7 for a discussion of **illuminance thresholds** applicable to the meteorological observer and to the pilots.

2.3.3 Luminance Contrast Threshold:-

The minimum **luminance contrast** at which an object 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 and the criteria which are used to determine if the object is "visible", and the observer's knowledge of the location of the object. See Section 4.2.1 for a discussion of **contrast thresholds** applicable to the meteorological observer and to the pilot.

Symbol: ε (epsilon)

2.3.4 Field Factor:-

The ratio of the threshold applicable to operational conditions with unstructured viewing to the threshold obtained under laboratory conditions using a forced choice response, a simple background, with the observer knowing where and when to look for the target is frequently designated as the **field factor**. Field factors are usually of the order of 2 to 20, depending upon the criteria applied [51, 118].

2.3.5 Allard's Law:-

An equation relating the illuminance produced by a source of intensity I on a plane normal to the line of sight at a distance x from the source and the atmospheric transmissivity [3, 4]. The equation relating these parameters is:

$$E = IT^x/x^2 \tag{2.15}$$

A uniform atmosphere which is not spectrally selective is implied.

2.3.6 Koschmieder's Law:-

An equation relating the apparent contrast, C_x, of an object viewed against a sky or fog background, its inherent contrast, C_o, and the atmospheric transmissivity [78, 79]. The equation relating these parameters is

$$C_x = C_o\ T^x. \qquad (2.16)$$

Note that, since the transmissivity, T, is never less than zero, C_x and C_o will always have the same sign. Hence in mathematical manipulation of equation (2.16) all contrasts may be considered as being positive. This is necessary when logarithms of both sides of the equation are taken.

2.3.7 Visual Range (V):-

The maximum distance, usually horizontal, at which a given object or light is visible under particular conditions of atmospheric transmission and background luminance. Photometric data describing the object or light in question, and the viewing conditions must be stated. Thus "the **visual range** of a light source (producing an intensity) of 10,000 candelas (in the direction of view) is x miles when the (atmospheric) transmissivity is 0.5 (per mile) by day (when the background luminance is 1000 footlamberts)". The parts of the sentence enclosed in parenthesis are frequently omitted.

Note: In maritime practice the term **visual range** is applied only to objects. The term "luminous range" is applied to lights.

Note: In the 1940's the term **visual range** was frequently used synonomously as or in place of the term **visibility** as defined in 2.3.13.

2.3.8 Runway Visual Range (RVR):-

As defined in Annex 14 [53] **runway visual range** is "the maximum distance in the direction of take-off or landing at which the runway or the specified lights or markers delineating it can be seen from a position above a specified point on its center line at a height corresponding to the average eye-level of pilots at touchdown.

"Note 1. A height of approximately 5 m (16 ft) is regarded as corresponding to the average eye-level of pilots at touchdown.

"Note 2. In practice, **runway visual range** cannot be measured directly from the position specified in the definition but is an assessment of what a pilot would see from that position.

"Note 3. For the purposes of the specifications in Annex 14 the specified lights are considered to be high intensity lights of the order of 10,000 candelas. Markers are not taken into account."

The U.S. definition of runway visual range in Federal Meteorological Handbook No. 1, Surface Observations, is given as "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."

2.3.9 Slant Visual Range (SVR):-

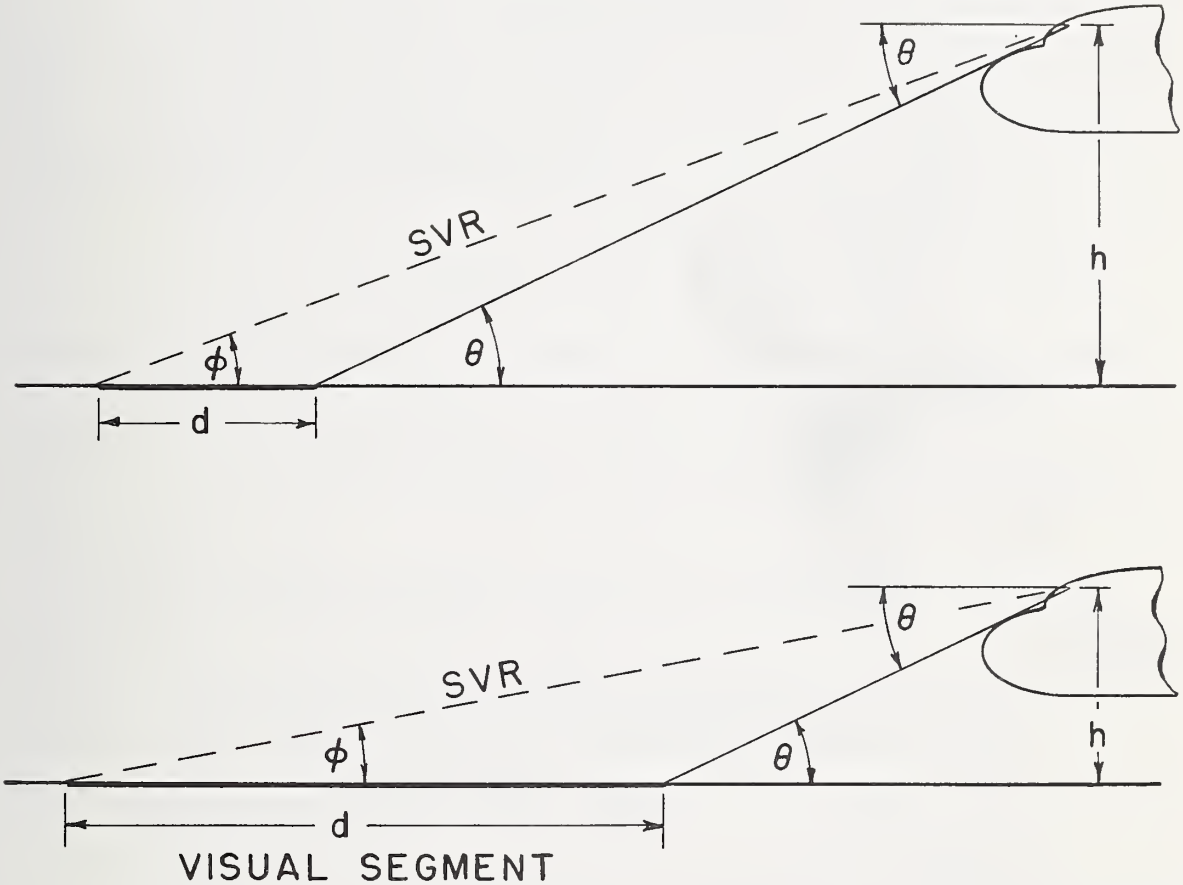
Fundamentally, **slant visual range** is the visual range of a specified object or light along a line of sight which differs significantly from the horizontal. If the transmissivity does not vary with height, then the visual range of a light or object along any slant path will be equal to the horizontal visual range of the light or object providing changes in background conditions do not have a significant effect. If the transmittance changes with height, the **slant visual range** is also a function of height and the height to which the stated **slant visual range** applies must be given.

Since the maximum depression of the line of sight over the nose of a typical aircraft is about 15°, the difference between the length of the slant path to the most distant object or light visible and the length of the projection of this path on the horizontal is usually not significant.

2.3.10 Visual Segment:-

The distance between the most distant light or object which is visible and the nearest light, or object which is not obstructed by the nose of the aircraft. The geometry is shown in figure 2.2.

Frequently, the concepts of **visual segment** and slant visual range are confused and a short **visual segment** is incorrectly interpreted as



$$d = SVR \cos\phi - h \csc\theta$$

$$d \doteq SVR - h \csc\theta$$

Figure 2.2 Geometry of the visual segment.

indicating that there is a large difference between the slant visual range and the horizontal visual range. In dense fog, a change in height can make a very significant difference in the length of the guidance segment. For example, in a normal approach, with a 15° cockpit cut-off and a uniform fog in which the slant and horizontal visual ranges are 1400 feet, at a height of 200 feet, the length of the **visual segment** is 627 feet and 6 or 7 lights of an approach light system (with lights spaced at 100-foot intervals) would be visible. However, at a height of 260 feet, the length of the **visual segment** is 395 feet and only 3 lights would be visible. The effects of change in height are even more pronounced if the fog intensity increases with height, as it often does.

2.3.11 Contact Height (Vertical Contact Height):-

The height at which visual reference with recognized lights or objects on the surface can be established sufficiently to permit visual determination of the ground plane and position.

2.3.12 Approach Light Contact Height (ALCH):-

The concept of approach light contact height is defined by Eggert [34] as,

> "The height above ground at which a pilot making an ILS or GCA approach can expect to see at least a 500-foot segment of the approach light system, with certain probabilities".

2.3.13 Visibility or Meteorological Visibility:-

The term **visibility** is used for two concepts in describing atmospheric conditions:

a. As a qualitative term to describe the clarity of the atmosphere, as "in periods of good visibility".

b. As a quantitative term to express the clarity of the atmosphere in units of distance.

In Federal Meteorological Handbook No. 1 [36], **visibility** is defined as, "the greatest distance at which selected objects can be seen and identified." Dark or nearly dark objects viewed against the horizon sky should be used by day and unfocussed lights of moderate intensity (25 cd) should be used by night. The Fourth (1971) Edition of the WMO "Guide to Meteorological Instrument and Observing Practices" [128] gives essentially the same definition. This is, of course, U.S. practice and the NBS transmissometer was calibrated using these criteria.

However, in most countries **visibility** and **meteorological visibility** at night have been reported as the distance at which a black object viewed against a sky background would be seen if it were day. This usage satisfies the requirements of the meteorologist since it yields a one-to-one correlation with atmospheric transmittance and a change from day to night does not produce, by itself, a change in the **visibility**. However, it is operationally unsound. A prominent British lighting engineer once stated that the reaction of pilots when this meaning of nighttime **meteorological visibility** is explained to them, is one of incredulity mixed with resentment. One must constantly keep in mind this difference in usage when interpreting reports and discussions of those who are not residents of North America.

As stated in definition 2.3.7, during the 1940's there was a move, led by Middleton, to use the term **visual range** for the concept of **visibility** as defined above, and many papers and reports prepared during that period, including those of NBS, use the term **visual range** in this context.

2.3.14 Meteorological Optical Range (MOR):-

The length of the path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp at a color temperature of 2700 K to 0.05 of its original value, that is, the length of the path in the atmosphere for which the regular transmittance is 0.05.

2.3.15 Meteorological Range (MR):-

The length of the path in the atmosphere required to reduce apparent contrast to 0.02 of the inherent contrast.

This definition is based upon the assumption of a contrast threshold, first made by Koschmieder, of 0.02. This contrast threshold was based upon laboratory conditions. Experience has shown that the use of this value was rather optimistic; however, it is still in frequent use.

2.3.16 Prevailing Visibility:-

The greatest visibility equal or exceeded through at least half the horizon circle, which need not be continuous, that is, the median visibility around the horizon circle.

2.3.17 Runway Visibility (RVV):-

The meteorological visibility along an identified runway. When a transmissometer is used for the assessment, the instrument is calibrated in terms of sighting a dark object against a fog or horizon sky background by day and lights of moderate intensity, about 25 candelas, by night. The use of **runway visibility** was superceded by the use of runway visual range in the early 1960's as the RVR digital readouts ("computers") were obtained.

It is now used when observations are made by a human observer from a position near the runway during transmissometer outages.

2.4 TERMS RELATED TO AIRCRAFT LANDING OPERATIONS

2.4.1 Runway:-

A defined rectangular area, on a land aerodrome, prepared for landing and takeoff of aircraft along its length.

2.4.2 Runway Threshold (Threshold):-

The beginning of the runway usable for landing.

2.4.3 Touchdown Zone (TDZ):-

The part of the runway immediately beyond the runway threshold where aircraft usually touch down; usually considered as being 900 meters (3000 feet) in length.

2.4.4 Approach Zone:-

The area immediately before the runway threshold over which the aircraft passes when making a landing.

2.4.5 Approach Lights:-

A configuration of lights located in extension of a runway before the threshold to provide visual approach and landing guidance to pilots.

2.4.6 Threshold and Runway End Lights:-

Lights placed to indicate the beginning and end of that portion of a runway usable for landing, respectively.

2.4.7 Runway-edge Lights:-

Lights installed along the edges of a runway marking its lateral limits and indicating its direction.

2.4.8 Runway Centerline Lights:-

Lights installed in the surface of the runway along the centerline indicating the location and direction of the runway centerline; of particular value in conditions of very poor visibility.

2.4.9 Touchdown Zone Lights:-

Barettes of runway lights installed in the surface of the runway between the runway edge lights and the runway centerline lights to provide additional guidance during the touchdown phase of a landing in conditions of very poor visibility.

2.4.10 Critical Height (C.H.):-

The minimum height above the ground at which an aircraft can execute a missed approach. Until mid-1964 the term critical height was used with the meaning now identified with decision height. At that time there was an abrupt change in usage presumably because of the realization that an aircraft should not descend as low as the critical height (as now defined) without visual reference.

2.4.11 Decision Height (D.H.):-

The minimum height above the ground to which a pilot making an instrument approach may descend without reference to lights or objects on the ground before executing a missed approach.

2.4.12 Operational Categories:-

Operational Performance categories as defined in Annex 10 [54] are

Operational Performance Category I: Operation down to 60 meters (200 feet) decision height and with a runway visual range not less than a value of the order of 800 meters (2,600 feet) with a high probability of approach success.

Note: In the U.S.A., FAA Order 6560.10 allows some Category I operations with a minimum RVR of 1800 feet if touchdown zone and centerline lights are available.

Operational Performance Category II: Operation down to 30 meters (100 feet) decision height and with a runway visual range not less than a value of the order of 400 meters (1200 feet) with a high probability of approach success.

Operational Performance Category IIIA: Operation, with no decision height limitation, to and along the surface of the runway with external visual reference during the final phase of the landing and with a runway visual range not less than a value of the order of 200 meters (700 feet).

Operational Performance Category IIIB: Operation, with no decision height limitation, to and along the surface of the runway without reliance on external visual reference; and, subsequently, taxiiing with external visual reference in a visibility corresponding to a runway visual range not less than a value of the order of 50 meters (150 feet).

Operational Performance Category IIIC: Operation, with no decision height limitation, to and along the surface of the runway and taxiways without reliance on external visual reference.

Note 1. -- The values given in feet are approximate rather than exact equivalents for those given in meters and they have been chosen on the basis of their operational significance in establishing runway visual range values.

Note 2 -- The term "decision height" is defined in the ICAO PANS-OPS and the term "runway visual range" is defined in Annex 14.

The terms CAT I, CAT II, etc. are frequently used to describe weather in which the runway visual range is within the following limits:

CATEGORY	Runway Visual Range Limits	
	Meters	(Feet)
I	800+	(2600 +)
II	400-800	(1200-2600)
IIIA	200-400	(700-1200)
IIIB	50-200	(150-700)
IIIC	-50	(-150)

Note: A runway light intensity of 10,000 candelas is assumed unless otherwise stated.

2.4.13 Instrument Runway:-

A runway intended for the operation of aircraft using nonvisual aids and comprising:

2.4.13.1 Instrument Approach Runway. An instrument runway served by a non-visual aid providing at least directional guidance adequate for a straight-in approach.

2.4.13.2 Precision Approach Runway, Category I. An instrument runway served by ILS or GCA approach aids and visual aids intended for operation down to 60 m (200 ft) decision height and down to an RVR of the order of 800 m (2600 ft).

2.4.13.3 Precision Approach Runway, Category II. An instrument runway served by ILS and visual aids intended for operations down to 30 m (100 ft) decision height and down to an RVR of the order of 400 m (1200 ft).

2.4.13.4 Precision Approach Runway, Category III. An instrument runway served by ILS (no decision height being applicable) and:

a.--by visual aids intended for operations down to an RVR of the order of 200 m (700 ft);

b.--by visual aids intended for operations down to an RVR of the order of 50 m (150 ft);

c.--intended for operations without reliance on external visual reference.

Note: The figures given in feet are approximate equivalents for meters (rather than exact equivalents). They were chosen on the basis of their operational significance in establishing runway visual range values.

2.5 MISCELLANEOUS TERMS

2.5.1 Arcata (California):-

This place name appears frequently in this report and in many other reports concerning tests in fog. The name refers specifically to what is now the Eureka - Arcata Airport. The airport is about seven miles north of the town of Arcata on the shore of the Pacific. It is reputedly the foggiest airport in the continental United States. During World War II it was first an Army Air Corps Airfield, later a Naval Auxiliary Air Station. In 1945 the Navy selected this site for conducting thermal fog dispersal experiments. During the period 1946-1950 the Landing Aids Experiment Station - operated under Air Force, Navy, CAA sponsorship - was located on the site. The Station was converted to a commercial airport in 1950 and has continued as a County Airport. In 1953 the National Bureau of Standards established a Visual Landing Aids Laboratory at the airport. This operation was terminated in 1972. However, a small staff is now maintained at the airport by a commercial engineering firm under FAA contract. In addition many organizations, both government and private, have used the site for short periods to conduct experiments in fog.

2.5.2 Ceilometer, Rotating Beam or Fixed Beam:-

An instrument system used for determining cloud height by solving the triangle formed by a light source, the illuminated spot produced on the cloud by the projector and a photoelectric receiver which detects the angular elevation of the spot. See Section 8.2. The term ceilometer is often used without modification for either a fixed beam or a rotating beam ceilometer.

2.5.3 Laser Ceilometer:-

An instrument which determines cloud height by measuring the elapsed time of a light pulse reflected off a cloud base. The receiver and laser source are usually positioned next to each other.

2.6 INDEX OF TERMS

3. CHRONOLOGICAL RESUME

3.1 INTRODUCTION

The purpose of this section of the report is to review briefly the history of the development and application of the runway visual range concept. This section is essentially a flow chart given without extensive detail. A detailed discussion of the pertinent parameters is given later in the report.*

The distance at which one can see and recognize objects and lights has been a very important factor in determining the safety and regularity of travel since ancient times, particularly in the operation of aircraft. Reports of the prevailing visibility have been made by Weather Service since the early days of cross-country flight. At that time, and even today, these reports have been based upon the observations of human observers. From the beginning, there has been a desire to replace these subjective observations with quantitative measurements, and by 1940 several types of visibility meters had been designed.

3.2 DEVELOPMENT OF THE TRANSMISSOMETER INITIAL PHASE

In 1940 the National Bureau of Standards was requested by the Civil Aeronautics Administration to develop a visibility meter suitable for routine use at airports. At that time the National Bureau of Standards was completing its development of the prototype ceilometer.**

The first model of the transmissometer was constructed. Then, as now, the transmissometer consisted of three units, an unmodulated light source operating at a fixed intensity, a receiver with an output in the form of pulses with the pulse frequency proportional to the illuminance on the receiver, and an indicator consisting of a counting rate meter. Figure 3.1 is an elementary block diagram of the 1941 instrument. It was field tested on Nantucket Island, Massachusetts

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**A glossary of terms is given in Chapter 2.*

***The development of the ceilometer is described in detail in Chapter 8.*

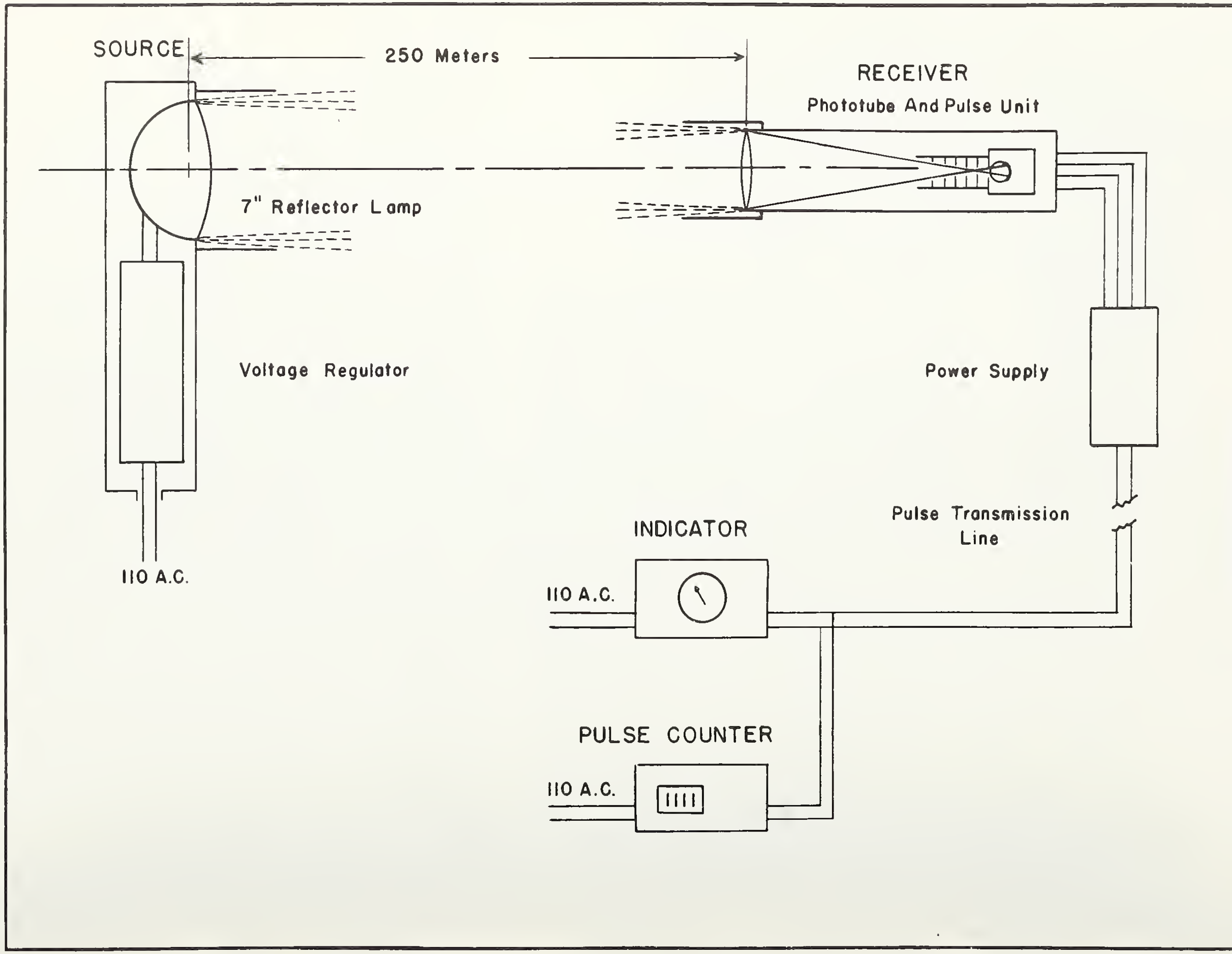


Figure 3.1 Elementary block diagram of first NBS transmissometer.

during the summer of 1941.*** Views of the field installation are shown in figure 3.2. During these tests numerous observations were made correlating the visual range of black objects by day and of lights by night with the transmissometer readings.

These observations confirmed the validity of Koschmieder's law for object visual range except that the value for the contrast applicable to weather observers was found to be 0.055 instead of 0.02, the accepted value at that time. The observations showed that at night the observer's illuminance threshold was increased by glow from the source being observed so that the threshold increased as the visual range decreased. An empirical relation between the visual range of lights by night and transmissometer reading was developed.

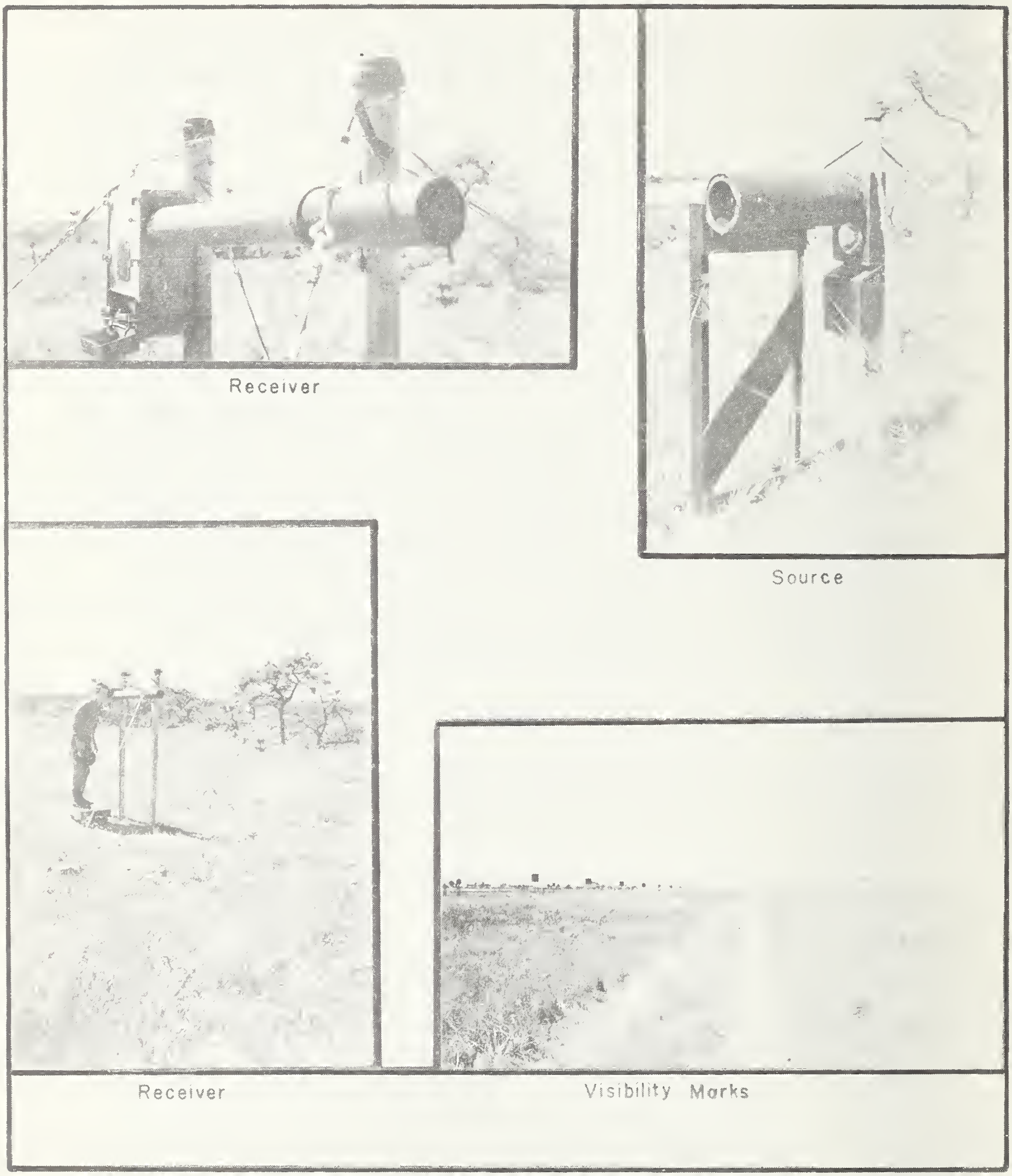
The transmissometer calibration curves for a 500-foot baseline instrument developed from the Nantucket study are shown in figure 3.3. The relations illustrated by these curves have been used since then in the United States to convert transmissometer readings to visibility and are the basis of tables A3 - 8A, B, and C of the present issue of Federal Meteorological Handbook No. 1, Surface Observations [36].

The Nantucket work also showed that spatial non-uniformity in atmospheric transmittance severely limited the applicability of a short baseline instrument in the assessment of prevailing visibility but that such instruments would be useful in the determination of atmospheric transmittance in restricted areas, for example, an approach zone.

3.3 DEVELOPMENT OF THE TRANSMISSOMETER 1941 - 1945

In the fall of 1941, the instrument was modified to provide internal calibration of the indicator, to permit operation of a recorder, and to allow the indicator to be located at a distance of several thousand feet from the field site. The instrument was then installed in the approach zone of runway 31 of the Indianapolis Municipal Airport where it was used by the C.A.A. Experimental Station in their tests of approach lights. The instrument remained at Indianapolis unitl it was turned over to the Navy for other work in 1943.

*** *The Development of the NBS transmissometer is described in detail in Chapter 6. A detailed discussion of field calibration of the instrument is given in Chapter 7.*



FIELD INSTALLATION

Figure 3.2 Transmissometer test bed on Nantucket Island, 1941.

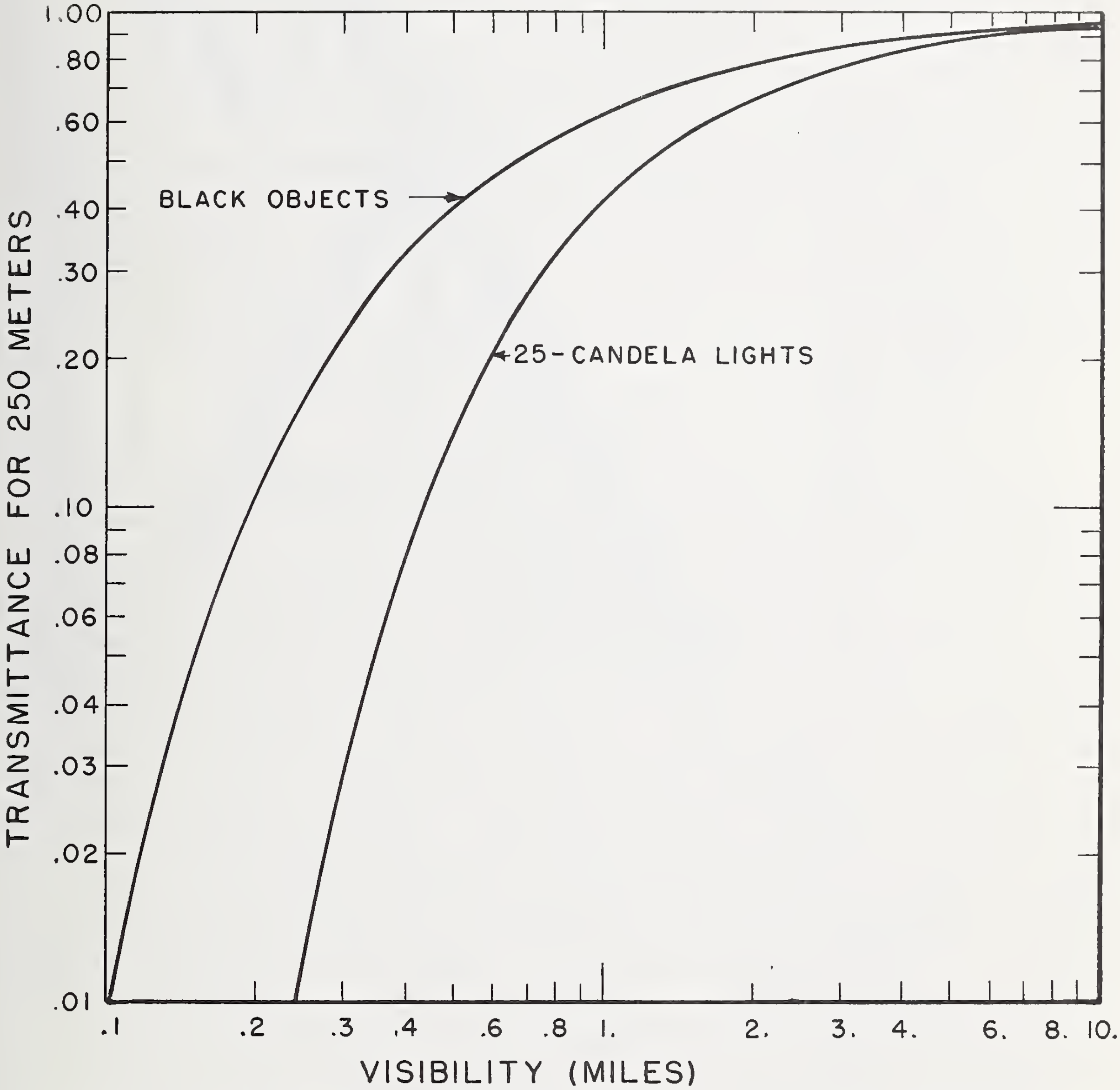


Figure 3.3 Transmissometer calibration curve developed at Nantucket. The visual range of objects is computed from contrast threshold of 0.055. The visual range of lights is computed from Allard's law assuming a light intensity of 25 candelas and an illuminance threshold of 0.084/V where V is the visibility in miles.

Progress during the war years was slow. During this period a transmissometer was installed at the Naval Air Test Center, Patuxent River and was used in conjunction with tests of airfield lighting equipment. In addition, three transmissometers with baselines of 2267, 3280, and 4000 feet were installed at Washington National Airport, the CAA Experimental Station, and the Naval Air Test Center, Patuxent River for correlation studies in visibilities in the 0.5 to 10 mile range. Very little quantitative information was obtained from these studies. The data indicated that changes in prevailing visibility were frequently apparent from the transmissometer records before they were recorded by the observers, and that spatial differences in fog density frequently produced large differences between the visibility indicated by the transmissometer and the observer's estimates of prevailing visibility.

3.4 DEVELOPMENT AT THE LANDING AIDS EXPERIMENT STATION

During the period 1946-1950, the Landing Aids Experiment Station (LAES) was operated at the Arcata, California, Airport, under the joint sponsorship of the Air Force, Navy, and Civil Aeronautics Administration to study methods of fog dispersal and approach light system configurations. For a detailed account of the meteorological instrumentation program see references [83, 84, 85 and 86]. All existing NBS-type transmissometers (6) were moved to LAES and, except for one, were used on 500-foot baselines along the instrument runway and in the approach zone to measure fog density in specific areas during tests. The other transmissometer was installed on a 3000-foot baseline to provide a measure of the prevailing transmissivity. The arrangement of instruments which evolved during the tests is shown in figure 3.4. Figure 3.5 is a montage showing the station and some of the equipment. The central transmissometer recording station is shown in figure 3.6.

Although its primary purpose was to provide test data, this assembly of instruments provided a unique opportunity to study the problems encountered in the operation and maintenance of the instruments. Throughout the period of operation of the station, refinements were made to improve the performance and maintainability of the instruments, and operating and maintenance techniques were developed.

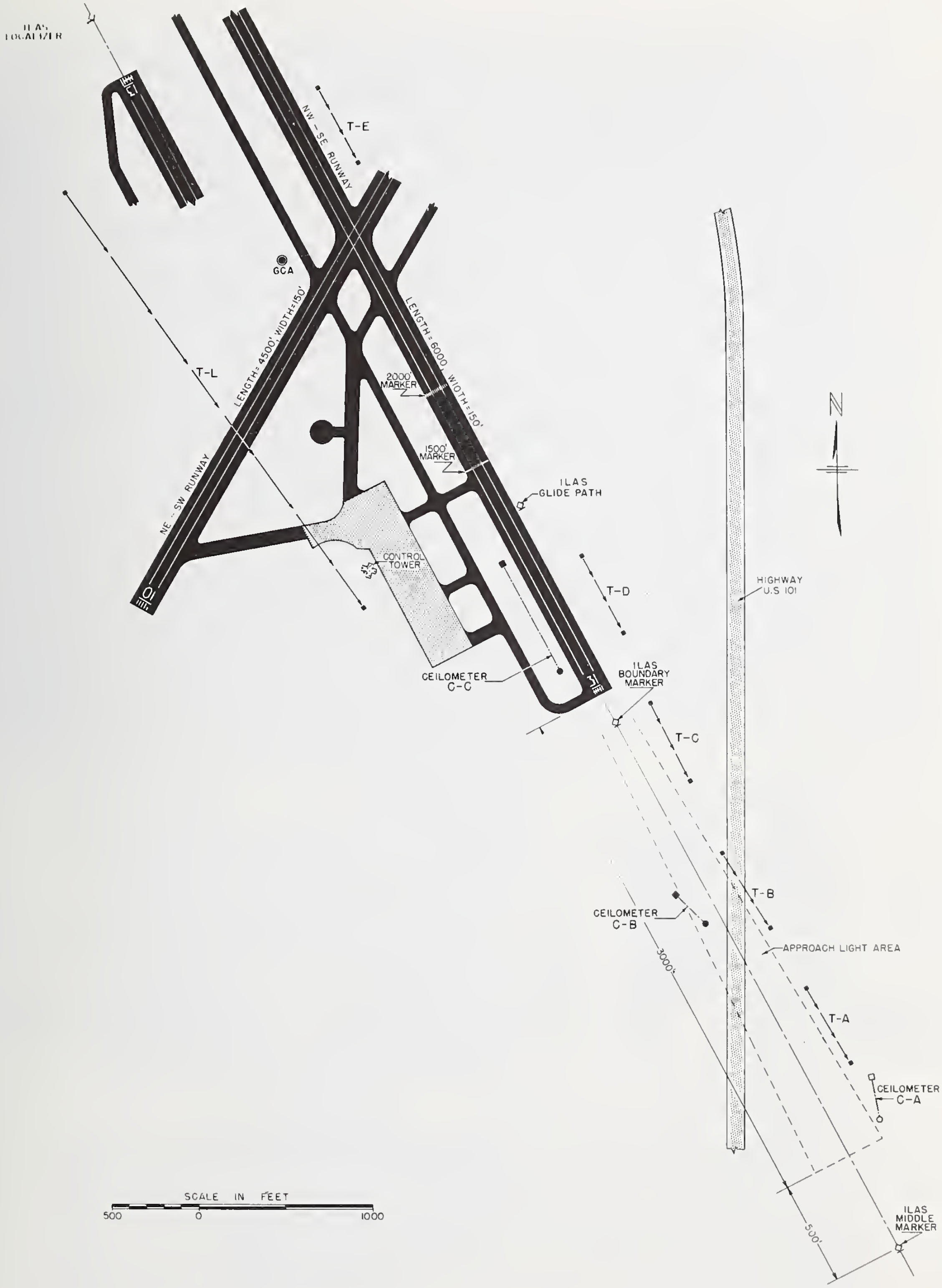


Figure 3.4 Meteorological Installations at the Landing Aids Experiment Station, 1948.

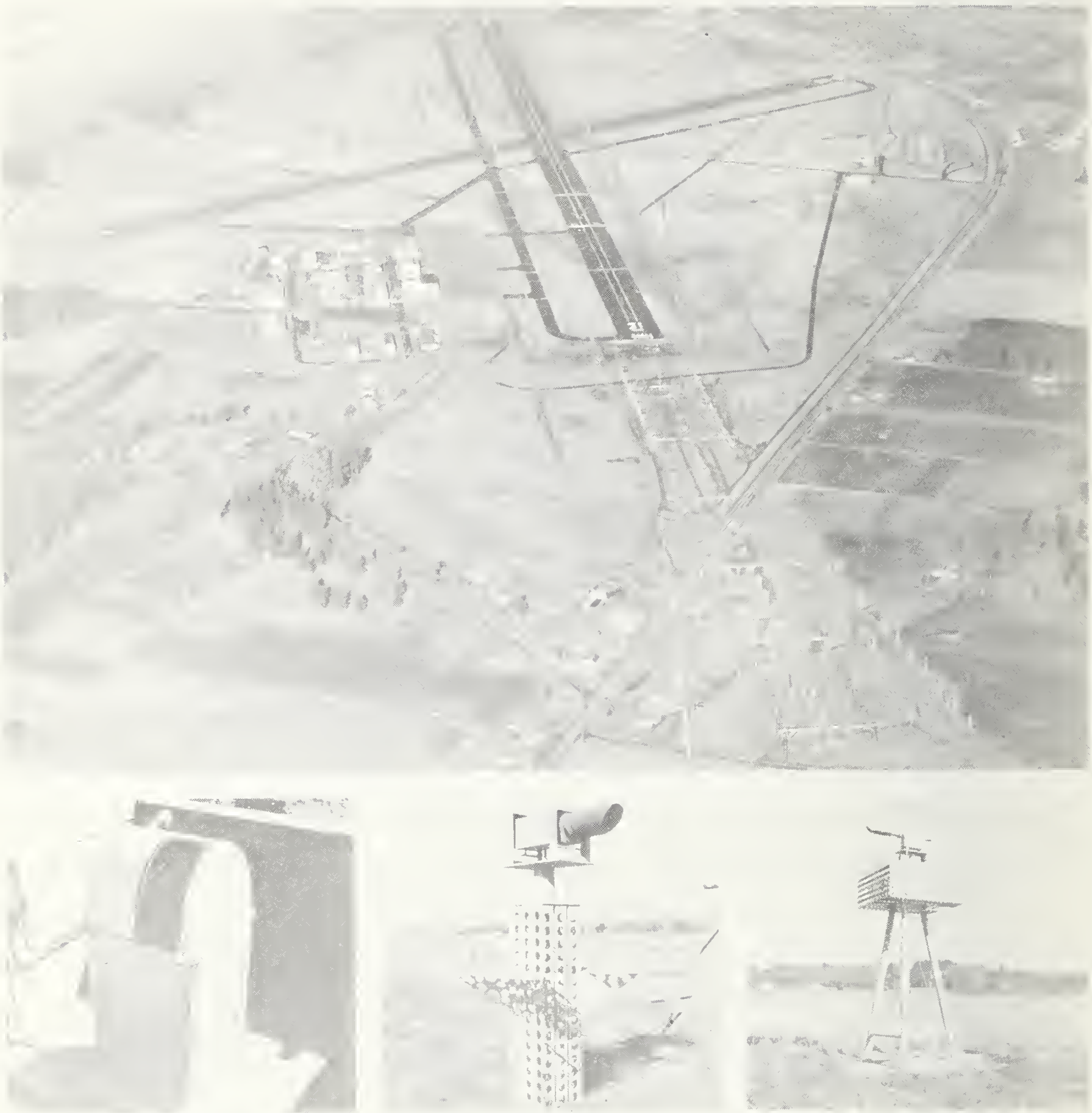


Figure 3.5 The Landing Aids Experiment Station in 1948. Shown also are: A ceilometer receiver, a transmissometer light source and a transmissometer receiver.

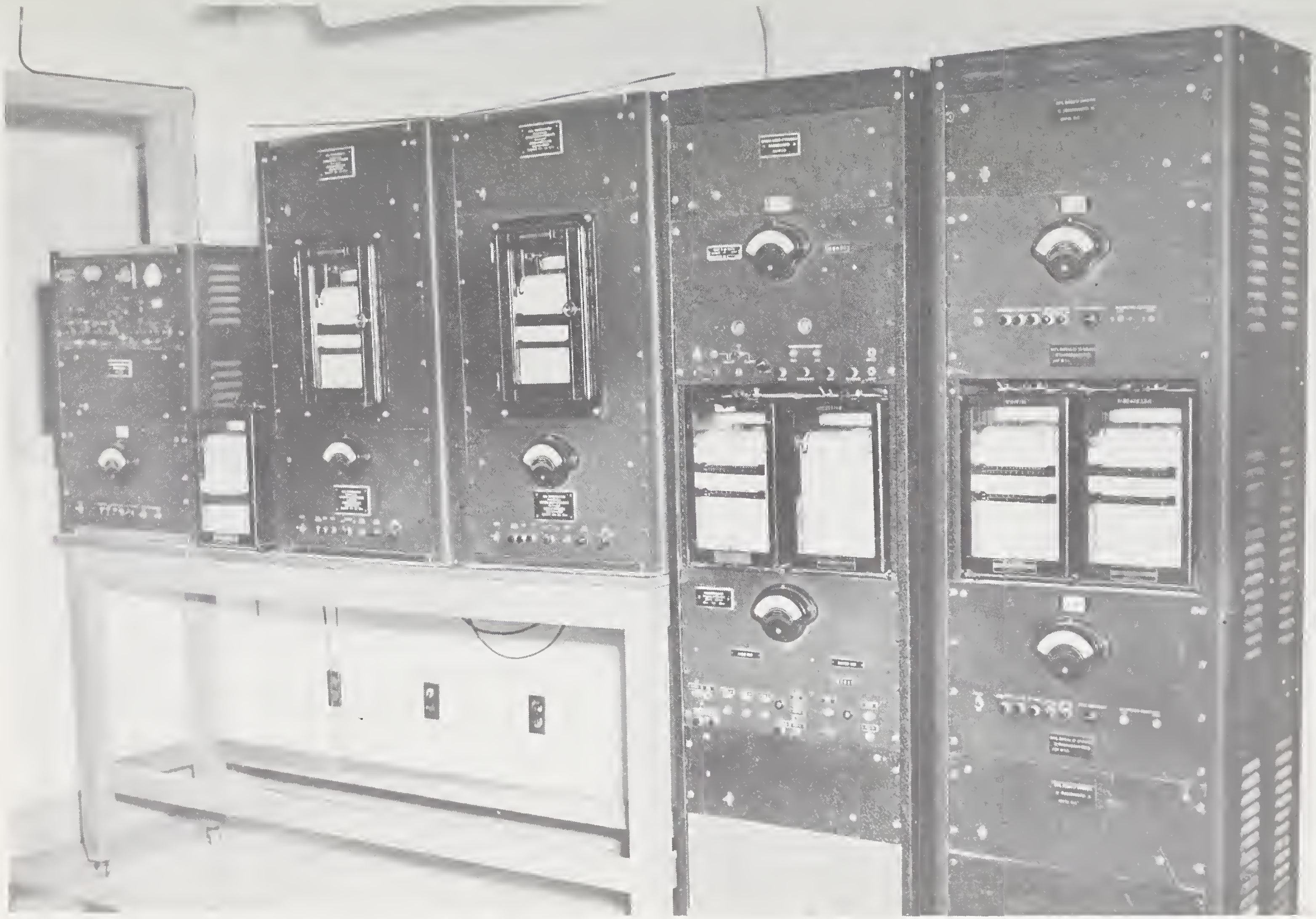


Figure 3.6 Central transmissometer recording position at the Landing Aids Experiment Station. The signal to the instrument in the extreme left was transmitted by UHF radio.

These instruments were provided with automatic sensitivity and pulse-counting controls so that they could provide automatically, with satisfactory accuracy, continuous records of transmittance ranging, at night, from 0.00002 to 1.00.

In addition to the regular operation of transmissometers, a dual-baseline transmissometer T-D_2 of figure 3.4 was operated in the touchdown zone during part of this period and transmissometer equipment was adopted to automatically control the intensity of lighting systems, satisfactorily controlling the intensity of the runway edge lights during the 1949 test season. A pictorial block diagram of the automatic intensity control system is shown in figure 3.7.

Some of these transmissometers were still in operation at Arcata when the NBS Visibility Laboratory was closed in 1972.

The array of instruments at the station was an excellent source of data regarding the temporal and spatial variations in fog density. Large random and systematic differences were found, confirming the data taken at Nantucket and elsewhere. An example of the spatial and temporal variations in fog density is shown in table 3.1. In this table the columns headed T-A, etc., show the visibilities computed from transmittance measurements of the indicated transmissometer. Locations of the transmissometers and the observers are shown in figure 3.4.

Although the purpose of the installation of transmissometers at LAES was not to test their use as visibility meters at airports, during the flight tests observers reported the horizontal visual range of selected objects or lights periodically, and pilots reported their visual contact height and the visual segment of the approach and runway (edge) lights during an approach and touchdown. These data formed an extensive data base correlating visual observations with transmissometer measurements.

The blockade of Berlin began in the summer of 1948 and the renowned airlift was started. The very high flight frequency required that after a missed approach an aircraft return to its base without making a second approach. This procedure imposed high demands on the accuracy of weather observations, and the existing routine procedures using visual

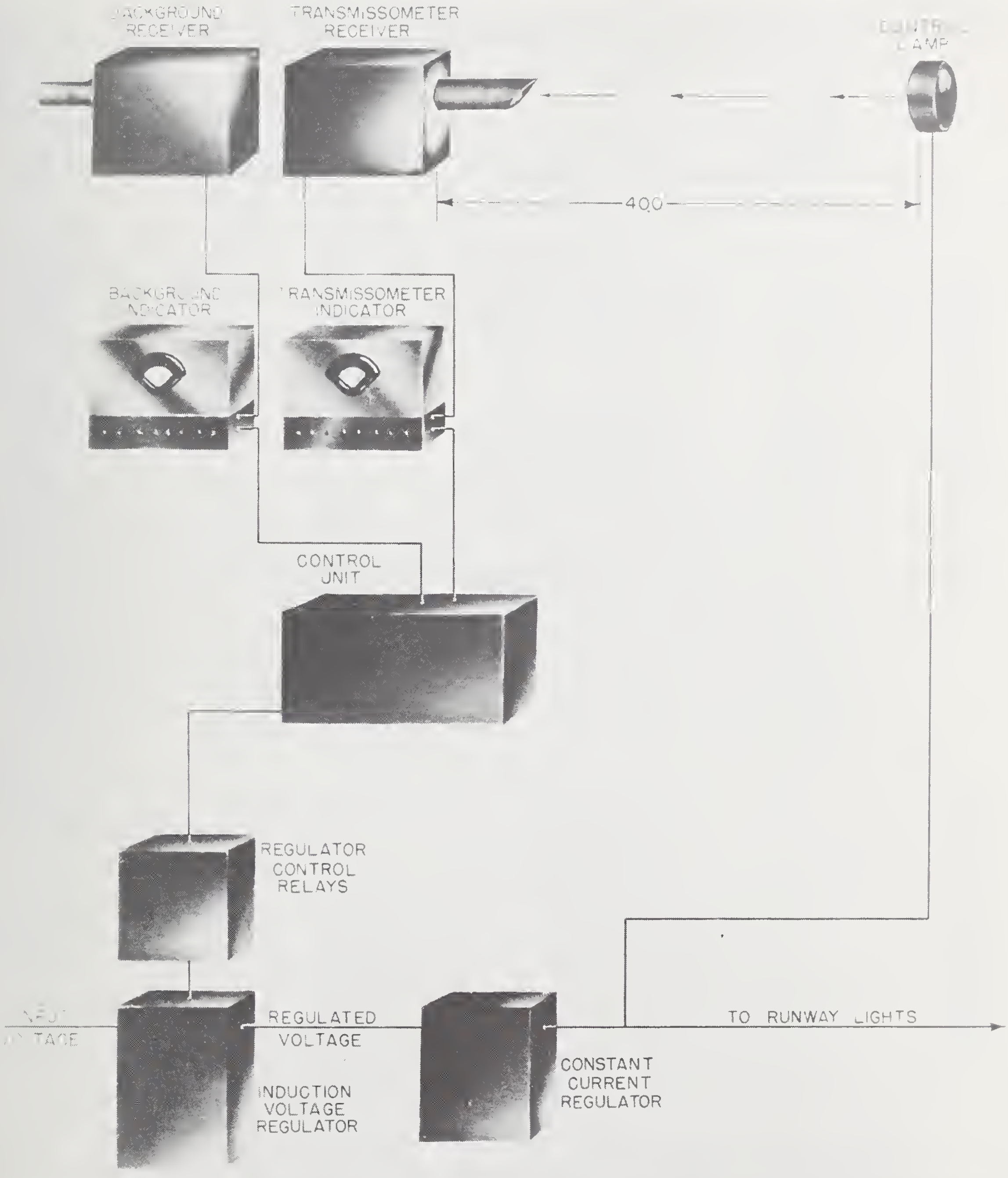


Figure 3.7 Automatic runway-light intensity control system at the Landing Aids Experiment Station.

TABLE 3.1

VISIBILITY CONDITIONS

LAES Flight Test No. 49-23

Time	Visibility in Feet							
	Outer Approach Observer Visibility North	T-A	T-B	T-C	Threshold Observer Visibility South	Threshold Observer Visibility North	T-D	T-E
0829	5000	3900	3600	3900	4500	6000	5600	3400
0838	6000	6500	3900	4600	5000	5000	11000	2500
0846	5000	8400	5900	4600	5500	4000	2100	1200
0856	3000	8400	3000	1300	2500	2000	1500	1200
0906	2500	2600	1800	1500	2300	1800	1400	2000
0916	2200	2100	2100	1800	3000	3500	5700	850
0926	2000	1800	1700	2000	2500	3200	3000	600
0934	2000	2100	2100	1300	1800	2000	960	710
0944	1500	1000	1200	760	1400	1000	520	630
0954	1500	850	1200	840	1500	1000	680	360

Time	Visibility Relative to T-C						
	Outer Approach Observer Visibility North	T-A	T-B	Threshold Observer Visibility South	Threshold Observer Visibility North	T-D	T-E
0829	1.3	1.0	1.0	1.2	1.5	1.4	0.9
0838	1.4	1.4	0.8	1.1	1.1	2.4	0.5
0846	1.1	1.8	1.3	1.2	0.9	0.5	0.3
0856	2.3	6.5	2.3	1.9	1.5	1.2	0.9
0906	1.7	1.7	1.2	1.5	1.2	0.9	1.3
0916	1.2	1.2	1.2	1.7	1.9	3.2	0.5
0926	1.0	0.9	0.8	1.2	1.6	1.5	0.3
0934	1.5	1.6	1.6	1.4	1.5	0.7	0.6
0944	2.0	1.3	1.6	1.8	1.3	0.7	0.8
0954	1.8	1.0	1.4	1.8	1.2	0.8	0.4

observations were not adequate. Efforts to improve the situation were initiated immediately.

In November of 1948, Mr. G. H. Stocker, Meteorologist of LAES, suggested to the Chief of the Air Weather Service that transmissometers located in the touchdown and approach zones of the instrument runway be used in conjunction with a ceilometer in the approach zone as a standard operational weather reporting procedure. The following reasons were cited [85];

"Observations at LAES, as well as at other airports, have indicated that in weather conditions at or below ceilings of 200 feet and visibilities of 1/2 mile, the irregularity and variability of the respective weather elements requires continuous, automatic, objective meteorological measurements that are actually representative of "pilot's weather" in the instrument approach zone.

"The meteorological instrumentation available at this time, with a few changes in placement and in operational methods, appears to be readily adaptable as a basis for the aforesaid development. The fundamental requirements in any such instrumentation appear to be as follows:

"a. Airport weather observations should be made along the actual approach (or take-off) path of the aircraft.

"b. Automatic, objective instrumentation should be utilized in making weather reports in order to eliminate inconsistencies resulting from individual variations and errors among human observers.

"c. Airport station weather reports should be revised in form to include the operational (or "pilot's") weather in the flight path of aircraft at least in the "Remarks" section of the report.

"With reference to "weather" resulting from the presence of an extremely low cloud deck*, it would appear that an installation consisting of one shortbase ceilometer and two shortbase transmissometers should be adequate to indicate and record the effective operational "weather" along a normal instrument approach zone and runway.

"*Other conditions, such as ground fog or heavy precipitation, may require addition consideration."

(The suggested configuration of meteorological instruments is shown in figure 3.8).

"The instrument is intended to measure:

"The ceiling and meteorological visibility in the area where the pilots of approaching aircraft first establish visual contact with approach lights or the ground; and the meteorological visibility in the touchdown zone along the runway.

"These are the two operationally critical areas in adverse weather conditions, since local ceiling and visibility conditions in these areas determine the amount of guidance available to the pilot from the ground plane, the approach lights, the runway-marker lights, and surface markings."

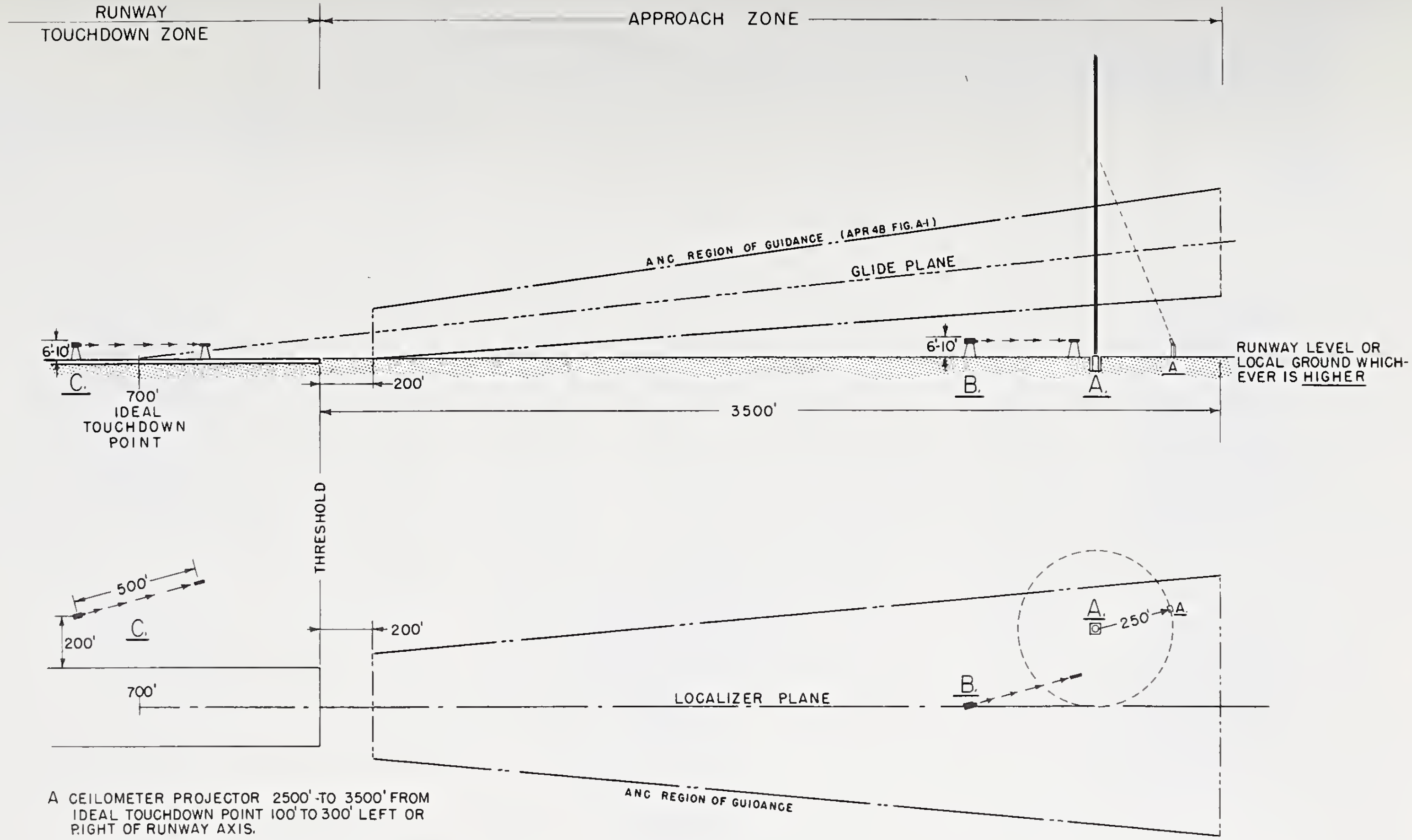
Although it had been tacitly assumed during their development that transmissometers would eventually be so used, this was the first explicit proposal for their use.

3.5 AIR FORCE APPLICATION OF THE TRANSMISSOMETER 1949-1953

The Air Weather Service accepted the LAES recommendation and requested that the transmissometers be moved from LAES to Berlin in the spring of 1949. However, further consideration showed that the Air Force was not prepared to provide logistic support and maintenance. Human observers were used instead.

Study of the concept continued, and its adoption as a standard weather reporting procedure was accepted by the Air Force in the early summer of 1949 although by that time the airlift had been discontinued. A program to obtain commercially manufactured instruments and to train Air Force personnel to maintain and operate the equipment was initiated, and during the 1949 fog season two groups of Air Force personnel were trained at LAES. However, it was not until the spring of 1950 that the procurement program was completed. At that time the National Bureau of Standards was requested to provide the Air Force with 25 instruments, spare parts, and an instruction book.

In June of 1950, a contract was awarded to the Crouse Hinds Company, Syracuse, New York, to construct 25 transmissometers with



A CEILOMETER PROJECTOR 2500'-TO 3500' FROM IDEAL TOUCHDOWN POINT 100' TO 300' LEFT OR RIGHT OF RUNWAY AXIS.

A CEILOMETER DETECTOR LOCATED ON 250' RADIUS ABOUT PROJECTOR.

B. APPROACH-ZONE TRANSMISSOMETER (500' BASE LINE) 2500' TO 3000' FROM IDEAL TOUCHDOWN POINT, WITHIN 300' OF, AND AT AN ANGLE OF AT LEAST 15° TO, THE RUNWAY AXIS.

C. TOUCH DOWN-ZONE TRANSMISSOMETER (500' BASE LINE) BRACKETING THE IDEAL TOUCHDOWN POINT, MINIMUM OF 200' FROM EDGE OF RUNWAY AND AT AN ANGLE OF AT LEAST 15° TO THE RUNWAY AXIS.

Figure 3.8 Locations of transmissometers and ceilometer proposed by Mr. G. H. Stocker of the Landing Aids Experiment Station, 1948 spare parts. The first instruments were delivered in June of 1951; tested at the National Bureau of Standards; minor modifications made; and type approval obtained in August, 1951. Although the instruments differed considerably in construction details (figures 3.9 and 3.10), the principles of mechanical and optical design, and of electronic circuitry were the same as those of the earlier instruments [103]. Concurrently, kits for modifying ceilometers to permit remote indication and to improve their response during periods of low visibility were being procured through other channels.

One transmissometer and a modified ceilometer were then given operational suitability tests at Eglin Air Force Base [2]. The primary conclusions of these tests were:

a. "Transmissometer-ceilometer equipment is operationally suitable for measuring cloud height (ceiling) and visibility in the approach and touchdown zones of instrument runways under temperate and extreme climatic conditions."

b. "The inclusion of two transmissometers in the system is necessary because of visibility variations between approach and touchdown zones."

c. "There is no appreciable difference in visibility observations made at the runway edge and as far as 400 feet from the runway edge."

Conversion from the transmissometer transmittance measurements to visibilities was done by means of the equations and threshold constants developed at Nantucket and verified by subsequent testings. In addition to conversion tables relating transmittance and day and night visibility, converters were supplied to be attached to the recorders, so that the charts could be read through them, and for desk use. A drawing of the desk converter is shown in figure 3.11.

Following these tests, the Air Force proceeded with the installation of modified ceilometers and the transmissometers procured by contract with the National Bureau of Standards. In designing these installations for

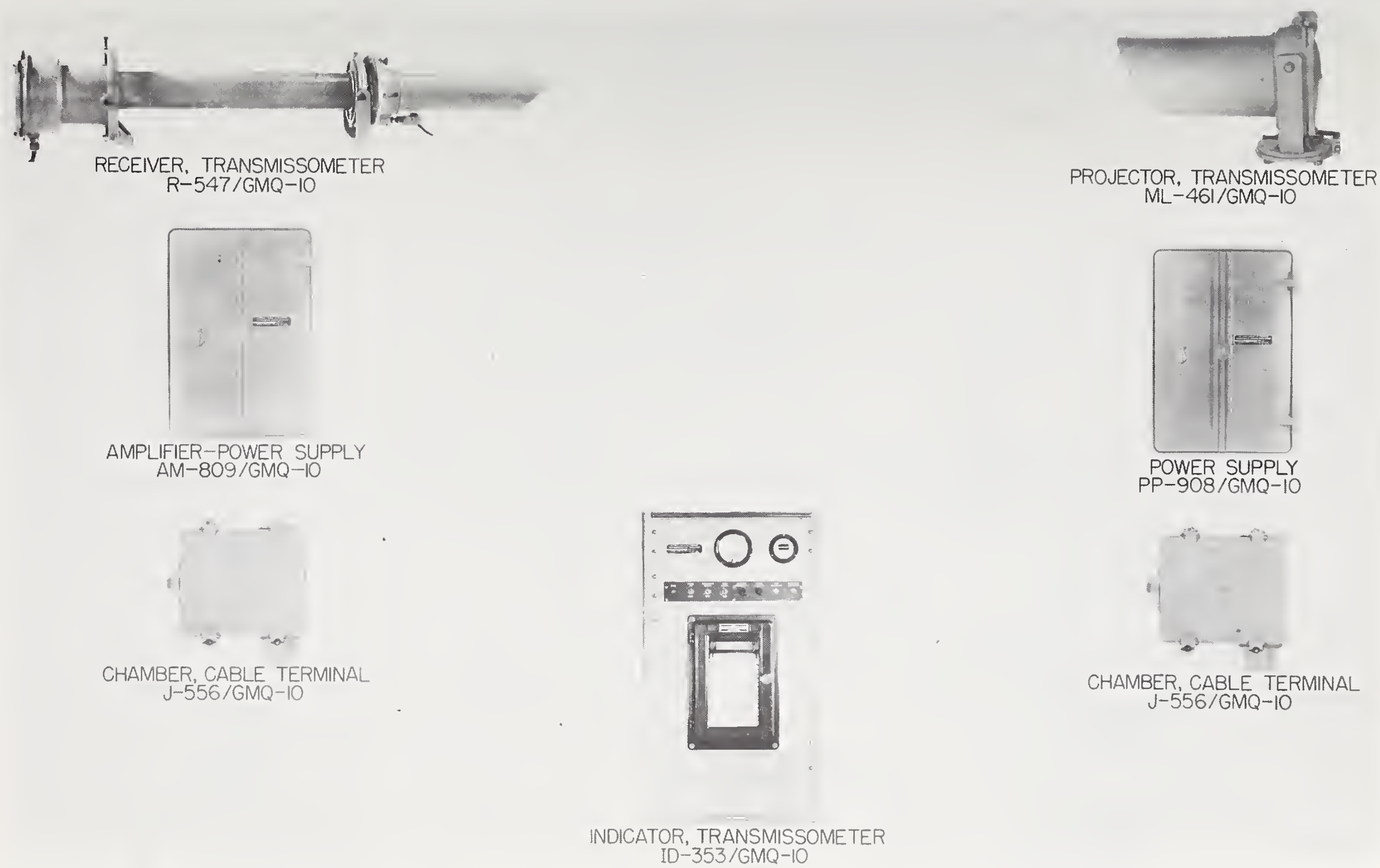


Figure 3.9 Transmissometer set AN/GMQ-10.

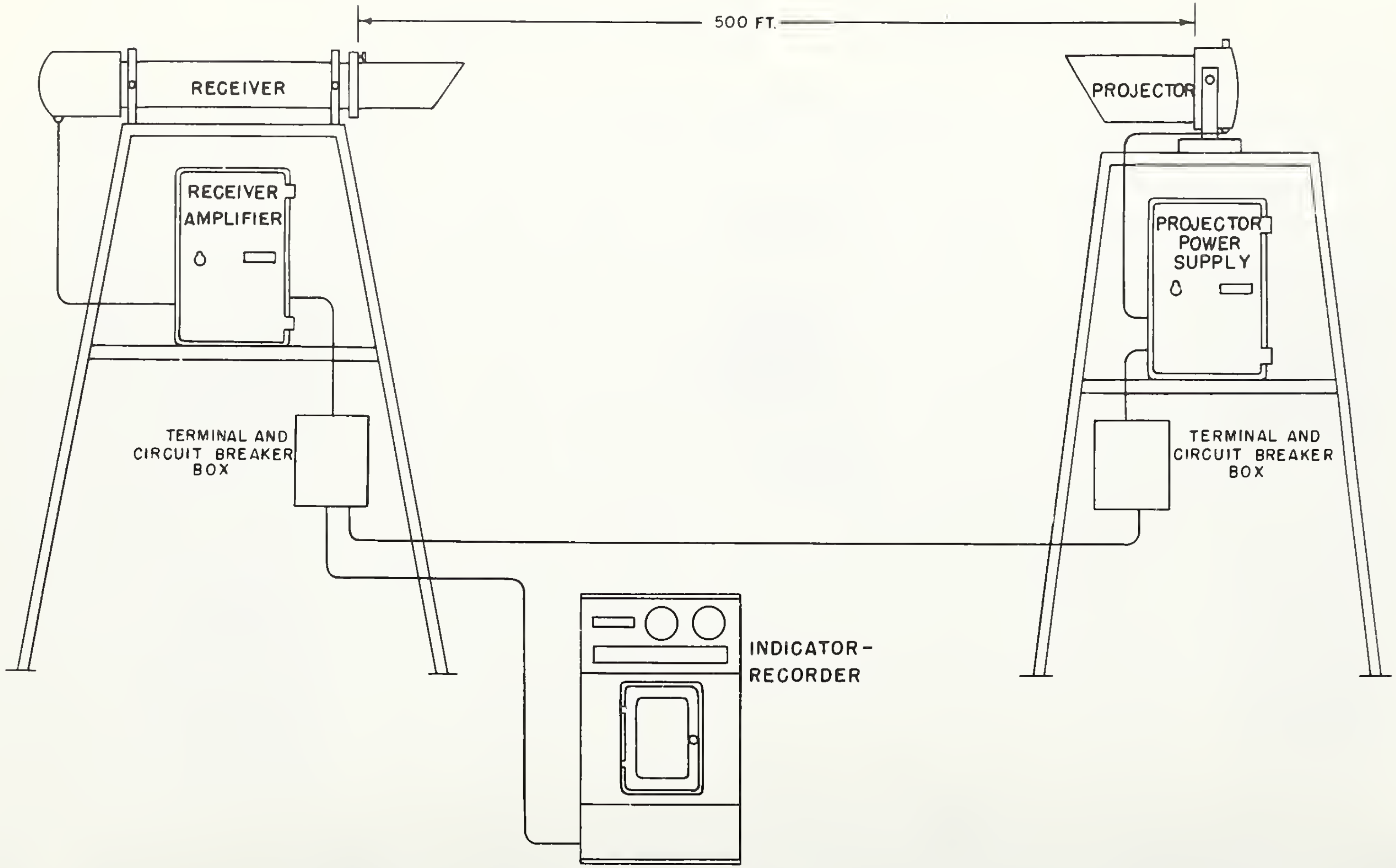


Figure 3.10 Transmissometer Set AN/GMQ-10, Schematic Arrangement

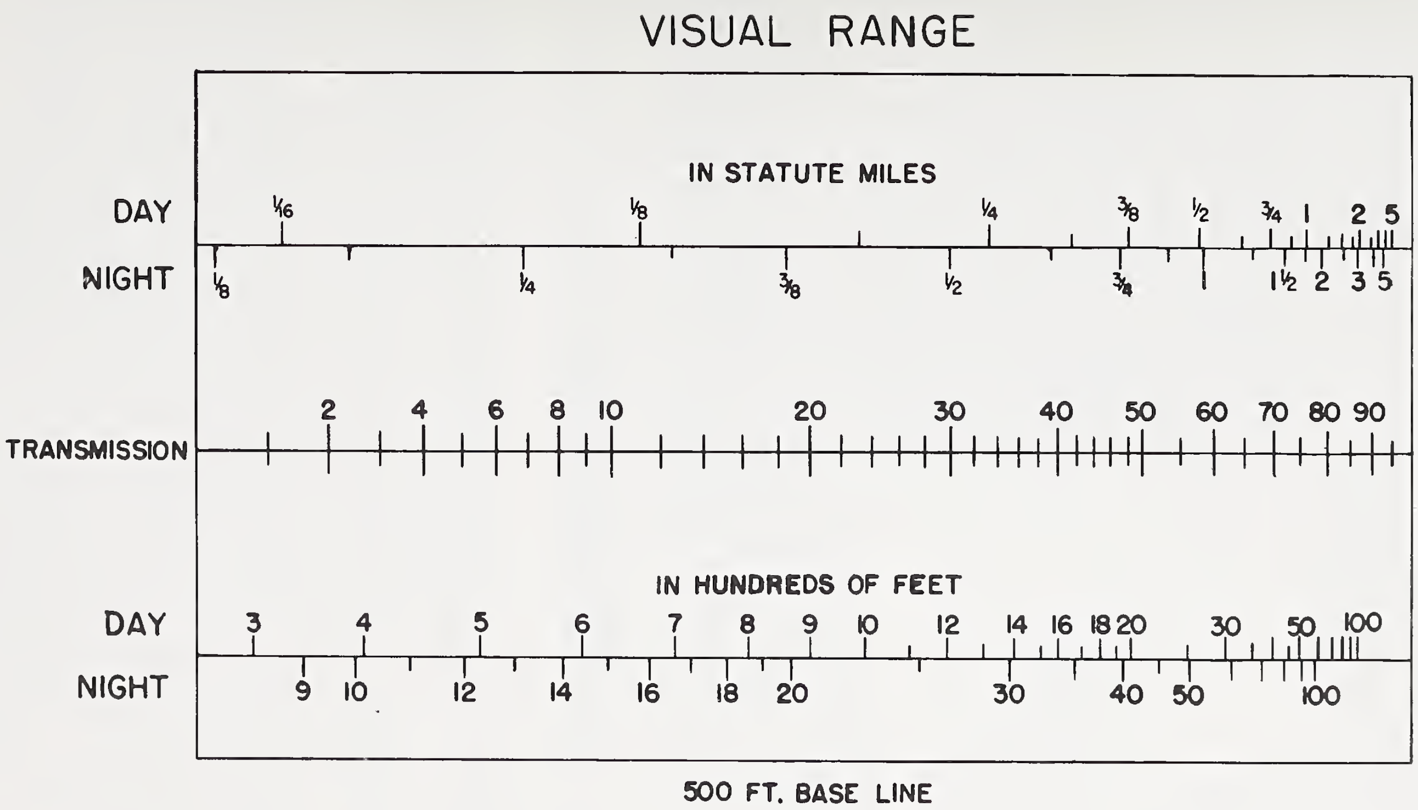


Figure 3.11 Transmittance - visibility conversion scale for chart recorders (1951)

16 of the bases, the Air Force followed the recommendations of the Weather Bureau (see section 3.7.2) and only one transmissometer was installed at each airport, near the touchdown zone. However, at two of the bases, the recommendations of LAES and Eglin AFB were followed and an additional transmissometer was planned for the approach zone [7]. By the spring of 1954, transmissometer installations had been made or were scheduled for the following bases:

Andrews AFB, Maryland
Brookley AFB, Alabama
Dover AFB, Delaware
Dow AFB, Maine
Ernest Harmon AFB, Newfoundland
Fairchild AFB, Washington
Langley AFB, Virginia
March AFB, California
McChord AFB, Washington
McClellan AFB, California (Two Sets)
McGuire AFB, New Jersey
Mitchel AFB, New York
Otis AFB, Massachusetts
Selfridge AFB, Michigan
Shaw AFB, South Carolina
Westover AFB, Massachusetts (Two Sets)
Wright-Patterson AFB, Ohio
Sewart AFB, Tennessee or
Moody AFB, Georgia (Alternate Site)

In August of 1954, the National Bureau of Standards conducted a two-week training course for Air Force operations and maintenance personnel.

By the end of 1954, the Navy had ordered 10 transmissometers.

3.6 APPLICATION OF TRANSMISSOMETERS TO CIVIL USE, INITIAL PHASE

3.6.1 Initial Applications:-

The application of transmissometers to operational use in civil aviation was, with two exceptions, more deliberate than in military aviation.

One of the exceptions was the authorization in 1949 of the use of minima of 1/4-mile visibility and 100-foot ceiling by Southwest Airways at Arcata provided transmissometers and a ceilometer, installed, as shown in figure 3.4, were in operation and the prescribed electronic and visual aids were available. Operations at these minima were terminated with the closing of LAES and the removal of the transmissometers and ceilometer in the summer of 1950. Transmissometers were reinstalled in 1951, but routine operations at the low minima were not reestablished.

The other exception was the use of transmissometers in conjunction with the fog dispersal (FIDO) system at Los Angeles Municipal Airport. Five transmissometers were purchased by the City of Los Angeles for this purpose, from the Crouse-Hinds Company, using a specification prepared by the National Bureau of Standards. This specification predated the specification used for the Air Force procurement. These transmissometers were installed along the runway on which the fog dispersal system was installed and used to measure the fog clearance produced.

3.6.2 Initial Studies by the Weather Bureau:-

The systematic study of the feasibility of civil use of the visibility-meter system proposed by Mr. Stocker as a replacement for the conventional visibility observations started with a Symposium called by the Weather Bureau on May 5 and 6, 1949. Because of its significance, the operational requirements for low visibility and ceiling measurements developed for the meeting are given below.

"1. To measure the visibility and base of low clouds in the approach zone between the inner* marker and one-half to three-fourths the distance down the ILS runway. This distance may vary from two to six miles depending upon airport size, surrounding topography, and obstructions.

2. Visibility measurements between zero and 1 mile along a straight line.

3. Base of low cloud measurement between zero and 500 to 1000 feet above the runway.

4. These observations will be relayed to the pilot on his final approach.

5. It is necessary that the observations be on a continuing basis and transmitted automatically via ground wire or micro-wave for a distance of one to six miles (to the Control Tower or other points of control).

---

*The outer marker was meant.

6. The values of base of low cloud and visibility should be recorded on a single dial indicator calibrated to indicate combinations of the two elements. These combinations will be determined from operational requirements and necessarily tempered by the limitations of equipment -----".

The meeting agenda is given in Appendix A. Some believed that there was a need for more data on the spatial variations of visibility and ceilings than that which had been obtained at the Landing Aids Experiment Station. Therefore, during the last half of 1949 the Weather Bureau, with the cooperation of the Civil Aeronautics Board, the Civil Aviation Administration, and the Air Transport Association, conducted a study at Washington National Airport of the differences in meteorological visibility reported by an observer from the Weather Observatory on the terminal building and visibility along runway 36 reported by an observer near the threshold. The two observation points were about 3000 feet apart. The observer at the terminal was about 70 feet above the ground, the observer at the runway site 10 feet above the ground. Ceiling measurements were made using a dual-projector ceilometer at the terminal and balloons or a ceiling projector at the runway site. The study confirmed the general opinion that the differences in visibility and ceiling were rather large and highly significant. Although the average ceiling was approximately the same for the two locations and the average visibility was slightly lower at the runway site that at the terminal, there were a number of instances when there were important differences. For example, although 27% of the visibility observations were identical, 15% of the runway visibility observations were 1/4 mile lower than the mirador observations and 10% were 1/4 mile higher.

Late in 1949 the organizations concerned determined that it was not economically feasible to solve the problem of spatial variations in visibility by placing an observer at the end of the runway during periods of low visibility and that instruments would be necessary.

3.6.3 Transmissometer - Ceilometer Program at Washington National Airport

During the period of the visibility correlation tests at Washington

National Airport, plans were developed for the installation of a transmissometer and a ceilometer there. The ceilometer was to be installed at the middle marker and a location near the glide path shelter was selected for the transmissometer. The indicators for the equipment were to be located in the Weather Bureau Marador Office. In their review of these plans some representatives of the Civil Aeronautics Administration and the Weather Bureau felt that the transmissometer should be located as close as practicable to the ceilometer. Others favored the touchdown zone site. The group was unable to reach agreement as to the most desirable location and plans were made to install a second transmissometer near the middle marker if one could be obtained. The equipment was procured and installed as shown in figure 3.12 in 1951. Note that the transmissometers used had 750 foot baselines. A second test site was established to test the rotating-beam and pulsed-light ceilometers at the Weather Bureau's Silver Hill Observatory.

In the fall of 1951 the Air Navigation Development Board (ANDB) agreed to sponsor a Weather Bureau project for "research and development work in methods of determining ceiling and visibility which affect the operation and control of aircraft during final approach and landing, particularly under low-ceiling, low-visibility conditions".

3.7 ANDB TESTS AT WASHINGTON NATIONAL AIPORT 1951-1953

Under ANDB sponsorship the Weather Bureau then established a project at Washington National Airport to study the meteorological aspects of the problem. At the same time a contract was let with the Sperry Gyroscope Company, with the Weather Buearu as a monitor, to conduct a program of flight-landing operations under low ceiling-low visibility conditions.

The work was given added impetus by Congressional hearings held in February and March of 1952 on aviation safety [41].

3.7.1 Application of Television:-

At these hearings there was considerable discussion of the feasibility of using television techniques to secure data to fulfill the operational

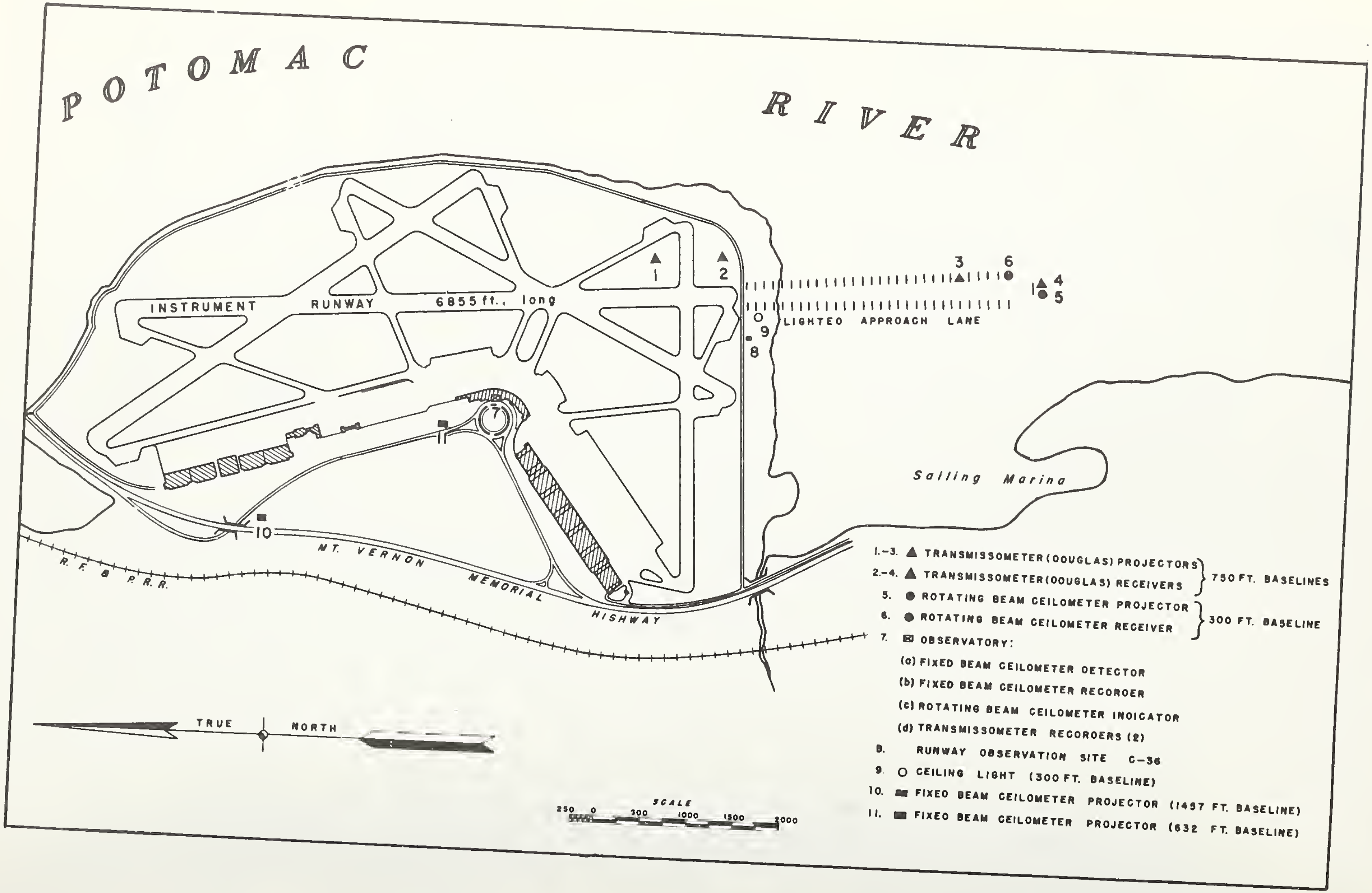


Figure 3.12 Instrument sites at Washington National Airport, 1951 [125].

need for better information at airports on visibility and ceiling conditions near the flight path, and an exploratory study was conducted as a part of the project at Washington National Airport. The camera was located at the approach end of the instrument runway (runway 36). The video signal was transmitted by microwave to the observatory in the terminal building where the receiver was located. During the tests all equipment was continuously monitored and adjusted by skilled operators for the "best picture". The experiment was designed so that comparisons could be made between the visibility determined by an observer in the observatory viewing the picture and an observer near the camera at the end of the runway viewing the scene directly. The results of the tests were negative. Although daytime visibility, using objects, could be determined "fairly well", the rendition of light sources near the limit of visibility was not representative of the visual scene. There were many engineering problems to be solved before the system was capable of continuous automatic operation [126]. At this point the study of the use of television systems was dropped.

3.7.2 Application of the Transmissometer-Ceilometer System:-

Of more importance than the tests of the application of television were the detailed studies made of the application of the transmissometer and ceilometer. A study was made of the relation between observed (meteorological) visibility and transmissometer data. From this study it was concluded that "the readings of the transmissometer, as calibrated by Douglas, show reasonably good agreement with (meteorological) visibilities reported by a nearby observer. There appears to be little difference between performance by day and night" [126]. The data obtained during stable and uniform low visibility conditions were analyzed to determine the contrast and illuminance thresholds of the persons making the visual observations. Both thresholds were in sufficiently good agreement with the transmissometer calibration thresholds that changes in the transmissometer calibration were not warranted. In addition it was found that operational measurement of the nighttime background luminance and consequent adjustment of illuminance threshold was not necessary. No twilight calibration was developed. See Section 4.4

for a more complete treatment of thresholds.

A study was made of the height of cloud base measurements using the rotating beam ceilometer. In this study it was found that an average of four measurements was required to yield an indication of the ceiling an approaching pilot would encounter. It was found that cloud bases were ragged and that cloud height used as an approach forecast must be considered as a zone, not a plane surface, and that the thickness of this zone may often be of the order of several hundred feet.

Tests of a French pulsed-light cloud height meter indicated that the instrument was not satisfactory because the pulse length made measurements of cloud height below 500 feet unsatisfactory.

The general conclusion of the study was that the transmissometer and rotating beam ceilometer were suitable for routine operational use. Operational use of the instruments was started December 15, 1952, using ceiling indications from the rotating beam ceilometer at the middle marker and visibility indications from the touchdown zone transmissometer for regulatory or control purposes whenever the touchdown zone visibility was 1½ miles or less. When the visibility indication of the middle-marker transmissometer was lower, the visibility indicated by this instrument was reported also. Experience soon demonstrated that changes in visibility occurred so rapidly that they could not be handled promptly by the regular weather observer and a direct indication was required in the control tower. Accordingly a five inch, 250° scale meter, calibrated as shown in figure 3.13, was installed in the tower for use by the air traffic controller. Note that a visibility of 1½ miles, which is about 10 times the length of the baseline, is the maximum visibility indicated on the scale, making the full 250° scale available for the operationally useful visibilities.

The day scale was used during twilight periods until the background luminance was so low that lights were clearly visible. When the visibility was varying rapidly, the mean value and the extremes were reported.

During these tests it was concluded that the additional transmissometer installed near the middle marker was not cost effective and it was

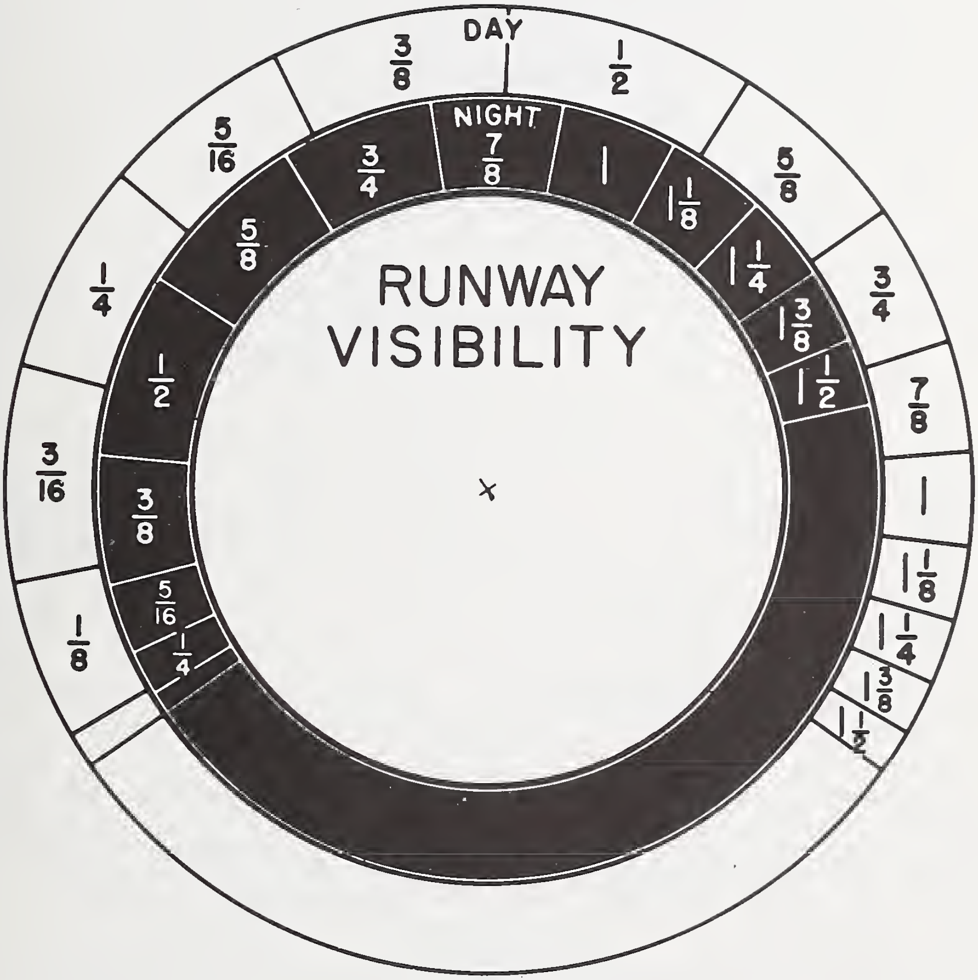


Figure 3.13 Runway visibility (RVV) scale used in early installation, for 750-foot baseline.

removed in September of 1953 for installation at Idlewild. (No documentation concerning the decision to terminate the use of the middle marker transmissometer has been located.)

The criterion used to judge the suitability of instrument program was approach success. Records of missed approaches at Washington National Airport during inclement weather were examined to determine if the operational use of the transmissometers and ceilometer had produced an improvement. Only approaches during periods where the visibility was less than one mile or the ceiling was below 500 feet were used in the analysis. Results of this analysis are shown in table 3.2.

Table 3.2

MISSED APPROACHES AT
WASHINGTON NATIONAL AIRPORT [126]

	Ceiling Less than 500 ft. and/or Visibility less than 1 mile		
	# of Approaches		
Periods of Operation	Attempted	Missed	Approaches Missed
Jan. 1, 1952-Dec. 15, 1952 (before use of runway observations)	983	63	6.3%
Dec. 16, 1952-Mar. 31, 1954 (after use of runway observations)	838	36	4.3%

From this analysis it was concluded that the data indicated that the low-weather instrument-approach success had been improved; the inference being that runway observations are more nearly representative of conditions experienced by the pilot in landing. Although some or all of the improvement might have been due to other causes, the results were encouraging.

3.8 ANDB TESTS AT MacARTHUR FIELD (1953) AND AT IDLEWILD (1954)

Except for the analysis of missed approach data, the Washington National Airport Studies were limited to observations from near ground level. The study at MacArthur Field, conducted by the Sperry Gyroscope Company and monitored by the Weather Bureau, was designed to complete the program. The objective of this study was to evaluate the transmissometer-ceilometer system in relation to the operational requirements of the instrument approach by correlating the measurements obtained from the instruments with what the pilot saw simultaneously from the cockpit during ILS approaches.

A commercially produced transmissometer was installed near the touchdown zone mounted at a height of 15 feet on stands of recommended design. See figure 3.14. Two ceilometers were installed, one at the middle marker site and the other in the approach zone near the threshold. A terrain illuminometer, thirteen visibility targets and lights for obtaining meteorological visibility, and 28 "pup tents" (see Section 3.10.2) were installed as visibility targets to obtain supplementary data. The installation in the aircraft consisted of two photometers, a motion picture camera aimed to photograph the pilots view, a mapping camera directed downward to photograph the terrain, a NASA type cloud detector, and a photo-panel to document aircraft instrument readings.

The pilot or copilot reported a) vertical contact, b) approach light contact, and c) threshold contact. The approach light was the earliest system consisting of 14 neon bars each having an intensity of about 1000 candelas.

Because the approach lights at MacArthur Field were low-intensity lights and the Sperry pilots were very familiar with the field and surrounding terrain, the flights at MacArthur Field were supplemented by flights at Idlewild, where a high-intensity approach-light system was installed. A total of 468 instrument approaches, 409 at MacArthur and 59 at Idlewild, were made in low ceiling and/or low visibility conditions.

The results of the tests are summarized in table 3.3 [126].

Figure 3.14 Transmissometer receiver (left) and light source (right) installed at MacArthur Field.

TABLE 3.3

Comparison of Observations Made from Standard Station, End-Of-Runway Station and Aircraft

Weather Classification	Day or Night	a	b	"a" minus "b" Minimum	"a" minus "b" Average	"a" minus "b" Maximum	% of cases "a" greater than "b"	Total number of cases
Low Clouds	both	vertical contact height	standard station ceiling	-140	105	365	89	113
		vertical contact height	end-of-runway cloud height	-290	66	335	76	97
		standard station ceiling	end-of-runway cloud height	-531	-51	131	34	97
Radiation Fog	day	threshold contact range	standard station visibility	-4,900	-1,468	2,100	14	58
		threshold contact range	end-of-runway visibility	-8,500	-763	3,100	20	39
Radiation Fog	night	threshold contact range	standard station visibility	-1,500	684	2,700	72	19
		threshold contact range	end-of-runway visibility	-2,700	-136	1,300	47	18
Low Clouds	day	threshold contact range	standard station visibility	-9,100	-2,128	1,800	10	61
		threshold contact range	end-of-runway visibility	-15,800	-3,737	800	1	56
Low Clouds	night	threshold contact range	standard station visibility	-31,400	-5,434	800	8	55
		threshold contact range	end-of-runway visibility	-23,300	-8,076	500	7	54
All	day	standard station visibility	end-of-runway visibility	-17,761	-691	5,610	50	125
	night	standard station visibility	end-of-runway visibility	-11,858	-1,003	4,500	35	91

NOTES:

1. All deviations given in feet.
2. End-of-runway cloud height was taken as the mean of heights corresponding to maximum response for 8 consecutive cycles on the rotating-beam ceilometer at middle marker. In case of multiple maxima, the lowest was used.
3. End-of-runway visibility was taken as the visibility corresponding to the mean transmissivity over three minutes obtained from transmissometer near the touchdown point.
4. Comparisons between standard station and end-of-runway visibilities include all cases where standard station visibility was $1\frac{1}{2}$ miles or less.
5. The largest deviations of end-of-runway visibility from standard station visibility occurred during nonhomogenous conditions, as shown by remarks in standard station observations.

[From Reference 126]

Conclusions drawn by the Weather Bureau were, in part, that the transmissometer-ceilometer combination provided a sound method for remotely measuring weather in the approach zone, but that optimum interpretation of the data required supplementary photometric measurements.

The single recommendation made in the report on the project was that a program of field tests at regular airline terminals with airline aircraft and airline pilots should be implemented to evaluate a method of reporting which incorporates photometric measurements in addition to the usual meteorological parameters.

The basic data obtained in the project provided important information regarding the manner in which conventional ceiling and visibility observations compare with pilot experience during an approach. The following general conclusions were drawn from a study of the data from the standard station and the in-flight data:

1. Ceiling is usually a conservative estimate of vertical contact height. In 89% of the cases vertical contact height was greater than reported ceiling. Vertical contact height averaged 105 feet higher than reported ceiling.
2. When low clouds are present, reported visibility is usually greater than the contact range of the runway threshold. In 91% of the cases this condition prevailed. The average difference was 2,100 feet (approximately 0.4 mile) for the day cases and 5,400 feet (approximately one mile) for the night cases.
3. When radiation fog is present, the contact range of the runway threshold and reported visibility agree fairly well on the average. Threshold contact range averaged 1,500 feet (about 1/4 mile) less than reported visibility in daytime and 700 feet (about 1/8 mile) greater than reported visibility at night. Although the average differences were not great, the extreme differences, both day and night, were about four times the average.

The comparisons showed that there was ample justification for the rather common belief that meteorological observations, as routinely made at present, do not accurately indicate conditions the pilot will experience if, as is frequently done, ceiling is interpreted as vertical contact height and visibility is interpreted as contact range of the runway threshold, or other slant visibility.

When the end-of-runway station data were compared with the in-flight data, the overall nature of the comparison was not greatly changed, although there were, of course, variations in the details.

The results of the MacArthur Field tests and those at Washington National Airport were sufficiently convincing that by April 1, 1954 transmissometer systems were in, or near, operational use at Idlewild, Newark, and Washington and scheduled for installation at the following airports:

La Guardia, N.Y.
Boston, Mass.
Philadelphia, Pa.
Pittsburgh, Pa.
Cleveland, Ohio
Chicago, Ill.
Detroit, Willow Run, Mich.
Kansas City, Mo.
Seattle-Tacoma, Wash.
Portland, Oregon
San Francisco, Calif.
Los Angeles, Calif.
Fort Worth, Tex.
Anchorage, Alaska

3.9 DEVELOPMENT OF THE RVR SYSTEM

3.9.1 Inauguration of Runway Visual Range Readout:-

Even as the runway visibility systems were being placed into operational use, plans were being made to convert to a system which indicated runway visual range instead of meteorological visibility. The request for further development was motivated by several factors: a) European practice in reporting RVR, b) a desire to report visibility conditions in units which were more representative of what the pilot saw during an approach and landing, and c) the desire to take into account the increased visual range obtained with high intensity approach and runway edge lights and to obtain authority to land in more dense fogs without lowering the visibility minimums. (The relative importance of these factors is uncertain.)

By mid-1955 plans had been made for an RVR installation at Newark, and the values of the parameters to be used in converting transmissometer readings to RVR had been fixed.

An intensity of 10,000 candelas was chosen as being representative of the in-service intensity of a high-intensity runway-edge light in the directions from which it would be viewed during a flare and landing. This intensity was later chosen by the Visual Aid Panel in their amendment of the definition of RVR. See Section 3.11.2. The method of determining the intensity to be used in assessing RVR was later adopted by the International Civil Aviation Organization. See Section 3.11.3. No consideration was given to the changes in intensity which result from dimming the lighting systems in conditions of less dense fogs.

No special tests were made to determine the night and day illuminance thresholds to be used in the conversion to RVR. Laboratory data were not applicable. The spread of the illuminance threshold values obtained from flight test data in fog, for example, the Landing Aids Experiment Station data, was so large - several orders of magnitude - because of the effects of non-uniformities in the fog density and reporting errors, that use of the mean or the median threshold values would have been of doubtful validity. Hence, the thresholds were based upon engineering judgements considering past experience and practices.

A value of 2 mile candles was chosen for the nighttime illuminance threshold. In the early days of aviation, an illuminance threshold of 0.5 mile candle was used [117]. In the 1940's, an illuminance threshold of 1 mile candle was used by some engineers both in the United States and in Great Britain. The increase was made in consideration of the increased losses in sloped, multi-element, "bird proof" windscreens, the increased number of lighted instruments in the cockpit, and the increased complexity of flying. A further increase was made to 2 mile candles for use in the RVR conversion to obtain a value which was conservative in nature.

It is interesting to note that in 1955 the Aviation Committee of the International Commission on Illumination (CIE) was considering the nighttime values of illuminance threshold applicable to aviation [72]. This choice was completely independent of the work in the U. S. on illuminance thresholds applicable to RVR. The CIE recommended a value of one microlux (2.6 mile candles) for the nighttime illuminance threshold.

> *It should be noted that neither the value of illuminance threshold chosen, 2 mile candles, nor the CIE value, was intended to be applied to the high luminance conditions which now exist over a runway with high intensity edge, touchdown zone, and center-line lights, operating at full intensity as has been implied by some recent ICAO documents* [58]. *An analysis of thresholds applicable to RVR is given in Section 4.4.8.*

A value of 1000 mile candles was chosen for the daytime threshold in a manner similar to that used in choosing the nighttime threshold. The 1955 meeting of the CIE recommended a value of 300 microlux (780 mile candles) for dull overcast conditions and 1000 microlux (2600 mile candles) for bright sunlight conditions.

> *The relative agreement between these two independent evaluations of illuminance thresholds is gratifying.*

An RVR scale, shown in figure 3.15, was prepared as a replacement for the RVV of figure 3.13 scale used at prior installations. Note that the scale is graduated in feet instead of fractions of a mile. This scale was based upon an intensity of 10,000 candelas, and the two thresholds, 2 and 1000 mile candles, discussed above. No consideration was given to the effects of dimming the lights or to the visual range of objects.

An 810-foot baseline was used at Newark because the location of taxiways prevented the use of a 750 foot baseline.

3.9.2 Reconsideration of Thresholds:-

The landing minimum was set at an RVR of 2600 feet with no statement of minimum ceiling. Experience with the RVR and the lighting system was so favorable that, in early 1957, the operators requested that a study be made of the feasibility of modifying the transmissometer

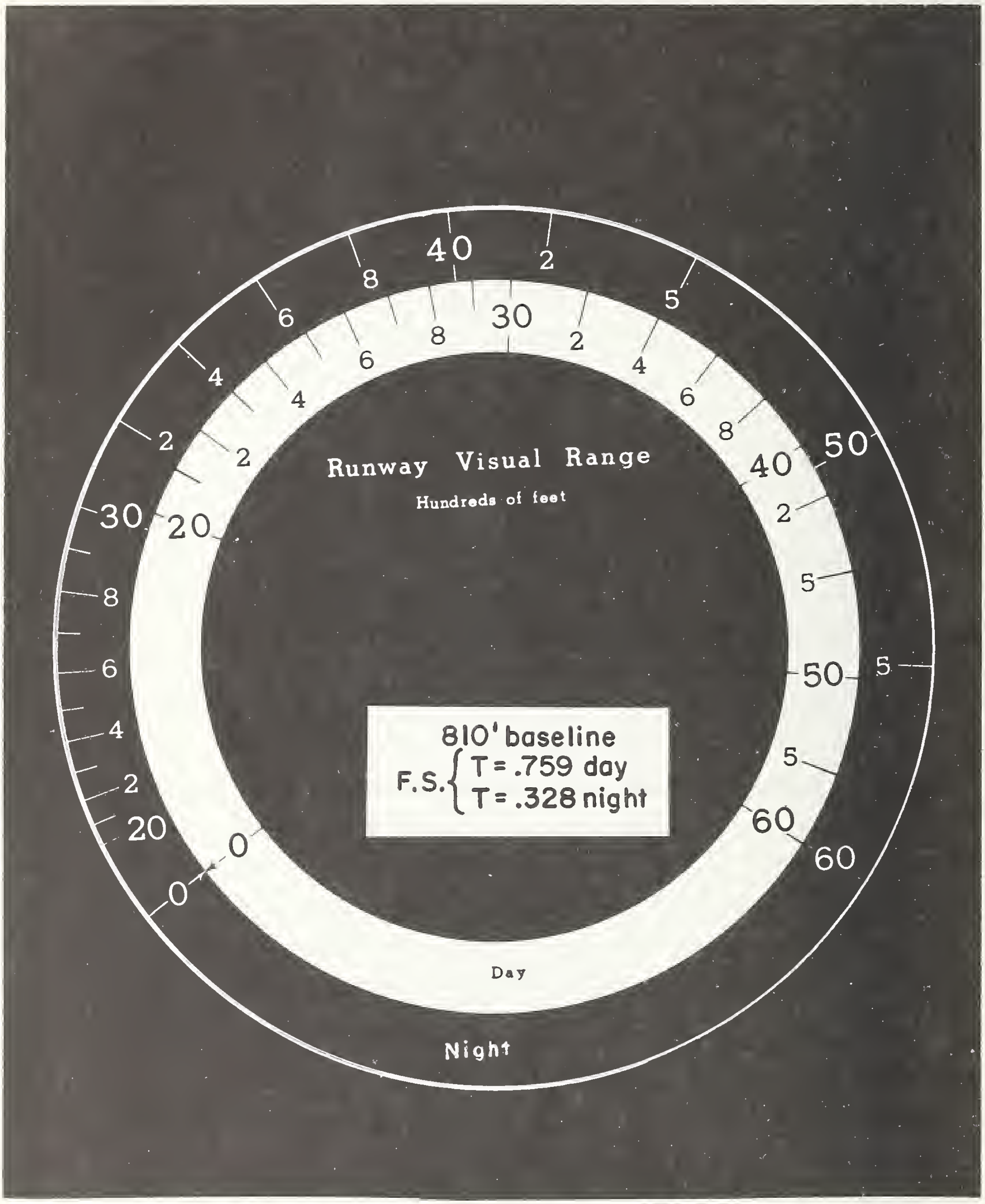


Figure 3.15 RVR meter scale used in control tower at Newark, 1955. This calibration is based upon 10,000 candela lights only.

RVR calibration stating that the calibration was too conservative. A small working group considered the problems and reviewed the factors considered in the choice of intensity and values of threshold illuminance.

The group concluded that the value of 10,000 candelas was representative of the intensity of the beam of the runway edge light in the direction of the pilot.

The group took into account the following factors in their discussion of illumination thresholds.

1) Thresholds obtained during the MacArthur Field tests.
2) Threshold obtained at Newark Airport, based on the sighting of the green threshold lights.
3) Internationally recommended values.
4) Reports that many pilots felt the present calibration to be too conservative.

The group found that for daytime thresholds:

1) The illuminance threshold for daylight of 1000 mile candles was more conservative than the 95% probability value observed at MacArthur Field.
2) It was very close to the 75% probability value observed at Newark. (Higher illuminance thresholds at Newark were expected because of the effect of the high intensity approach lights, which were not present at MacArthur Field.)
3) The 75% probability value had been suggested by pilots as an appropriate one.
4) The International Illumination Commission, meeting in Zurich in June 1955, recommended a value of approximately 780 mile candles for the illuminance threshold for a dull day.

The group found that for nighttime operations:

1) The night illuminance threshold of 2 mile candles corresponded to about the 40% probability level for MacArthur Field thresholds and to about the 20% probability level for thresholds at Newark based on sighting of the green threshold lights.

2) This indicated that the night illuminance threshold was somewhat optimistic. However, the group was reluctant to accept that concept in view of pilot reports to the contrary.

3) In support of the present value was the value of approximately 2.6 mile candles recommended by the International Illumination Commission for nighttime use. The 2.5 mile candle value was somewhat more conservative than the U.S. value of 2 mile candles, but the resulting difference in calibration was of no practical significance.

The group concluded that the evidence available was somewhat contradictory in nature and did not warrant a change in the present calibration of the transmissometer.

At this meeting it was suggested, informally, that, if the primary motive in suggesting a change in the RVR calibration was to permit landings in more dense fog, this should be accomplished directly by lowering the RVR minimum. Subsequently the RVR minimum was lowered to 2000 feet for airports having a "Configuration A" approach light system with sequenced flashing lights, and a high intensity runway edge light system with lights spaced at 100-foot intervals. (At that time Newark was the only airport meeting these requirements.)

3.9.3 Early Operational Use:-

By 1958 RVR systems with a meter readout were in operational use at Washington National, Idlewild and Boston in addition to Newark.

3.9.4 Approach Visibility Project at Newark:-

The approach visibility studies conducted at Newark during the period 1956 to 1958 by the Weather Bureau [34] and the Air Force [40] and at NAFEC during the period 1959 to 1962 [89] except as they relate to illuminance thresholds, are considered beyond the scope of this report and are not summarized.

3.9.5 Development and Application of the RVR "Computer":-

Even before the first RVR system with a meter readout was placed into service, plans were being made for the replacement of the meter readout with a digital display. The original request for proposal indicated that the same parameters were to be used for the digital display as were used for the meter calibration. The display was to be updated every thirty seconds, but there was not a requirement for averaging the transmittance over a period of time. The reporting increment was to be 100 feet from 2000 to 6000 feet.

These plans were considered by a working group comprised of representatives of the Civil Aviation Administration, the Weather Bureau, the Air Force, the airline operators, the airline pilots, and the National Bureau of Standards. The following design features were recommended by the group.

1) The nighttime and daytime thresholds then in use should not be changed. After considerable thought, adjustment of the daytime threshold for changes in background luminance and for twilight was rejected as not being cost beneficial.
2) An intensity of 10,000 candelas should be used as representative of the runway edge lights operated at full intensity but 2000 and 400 candelas should be used when the lights were operated at intensity steps 4 and 3 respectively. The applicable intensity should be determined automatically by the position of the intensity setting switch in the control tower.
3) The use of 100 foot increments was not practical because of the great variability of fog density with time. Studies of the temporal variation of RVR computed from NBS transmissometer records indicated that a 200 foot increment was suitable for RVR's below 4000 feet and 500 foot intervals were suitable for greater RVR's.
4) An averaging period of 45 to 60 seconds should be used. The averaging periods used at the Landing Aids Experiment Station and in the MacArthur Field tests of 4 and 3 minutes were considered too long to permit adequate representation of sudden changes in RVR, and periods less than 45 seconds were considered too short to permit adequate representation of RVR obtained by measurements of transmittance over a relatively short baseline.

5) The minimum RVR to be displayed should be considerably lower than 2000 feet. To accomplish this the length of the transmissometer baseline should be reduced from 750 to 500 feet.

6) Since in daylight, the meteorological range exceeded the RVR at high transmittances and the minimum visibility requirement for the jet aircraft then being introduced was in this transmittance region (4000 feet RVR or 3/4 mile meteorological visibility), the indicated RVR should be based upon the visual range of black objects whenever it exceeded the RVR. Otherwise the fog would be less dense under minimum conditions at RVR equipped airports than at airports using RVR or weather station observations.

7) The contrast threshold to be used in the computation of the visual range of black objects should be 0.055, the same as used for the RVV calibrations.

These criteria were accepted and procurement of computers was initiated.

The "computers" designed to these requirements were essentially memory banks of six sets of tables based upon the two thresholds and the three light intensities, with selection of the proper value of the appropriate table to be displayed controlled by the number of pulses generated by the transmissometer in a period of 55 seconds, an illuminance meter to select day or night scales and the position of the runway-edge light intensity-control switch. A graphical representation of the six scales used in the calibration of the computer is presented in figure 3.16. As many as five RVR readouts could be used with the computer.

3.9.6 Further Application:-

In mid-1962, RVR systems were in use at the following locations:

<u>Computer Commissioned</u>

1. Baltimore, Md.
2. Dallas, Texas
3. Los Angeles, Calif.
4. Montgomery, Ala.
5. New York (Idlewild), N.Y.
   Runway 4R
6. Newark, N.J.
7. Philadelphia, Pa.
8. Pittsburgh, Pa.
9. Portland, Ore.
10. Washington, D.C.

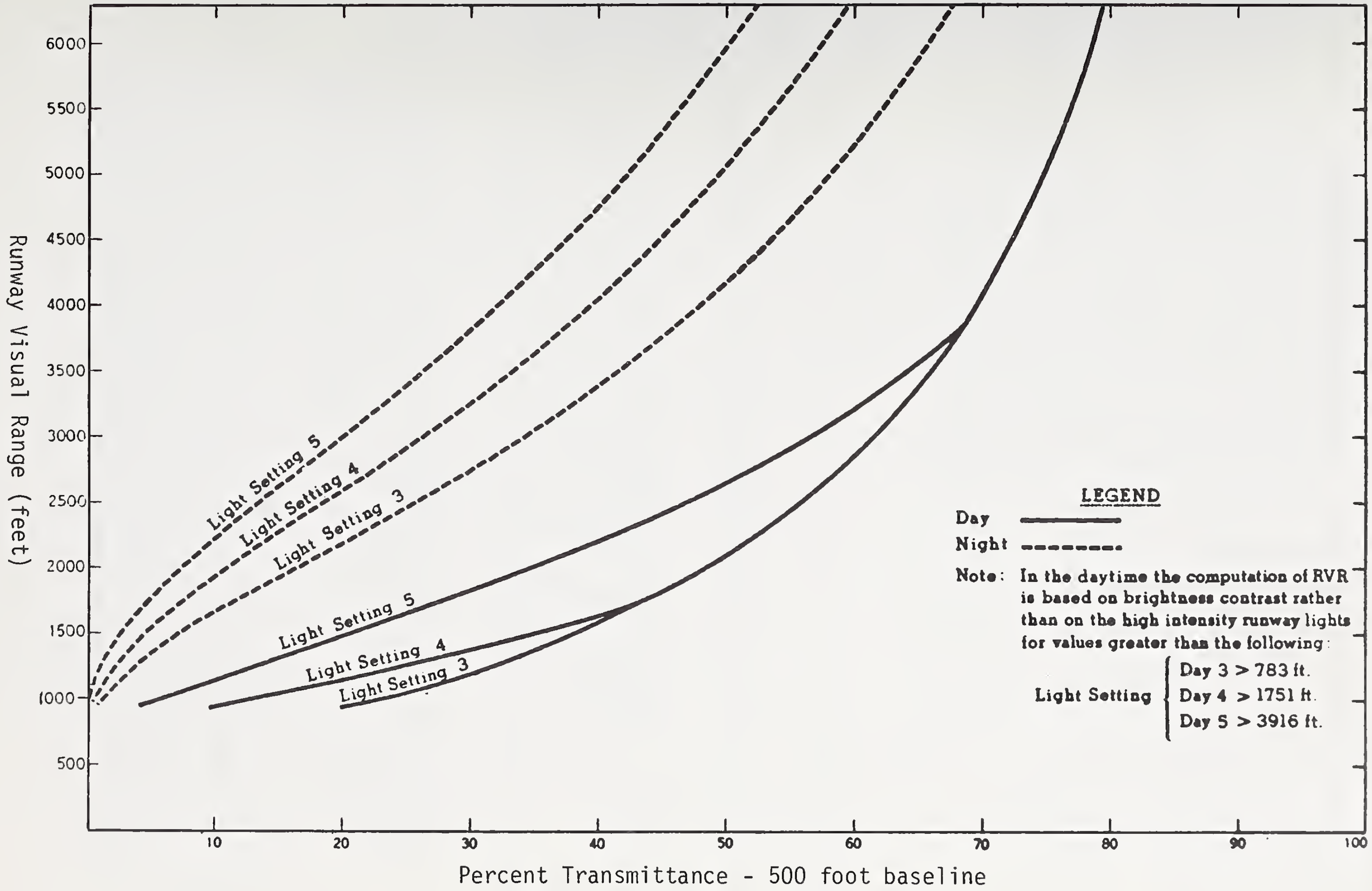


Figure 3.16 RVR calibration based upon three intensity settings and object visibility [35].

Meter Commissioned

1. Anchorage, Alaska
2. Atlanta, Ga.
3. Birmingham, Ala.
4. Boston, Mass.
5. Charleston, S.C.
6. Chicago (O'Hare), Ill.
7. Cleveland, Ohio
8. Columbus, Ohio
9. Denver, Colo.
10. Detroit (Met.), Mich
11. Detroit (Willow Run), Mich.
12. Fort Worth, Texas
13. Houston, Texas
14. Indianapolis, Ind.
15. Louisville, Ky.
16. Memphis, Tenn.
17. Milwaukee, Wisc.
18. Minneapolis, Minn.
19. Oakland, Calif.
20. New York (Idlewild), N.Y. Runway 31L
21. St. Louis, Mo.
22. Salt Lake City, Utah
23. San Francisco, Calif.
24. Seattle-Tacoma, Wash.
25. Spokane, Wash.
26. Tampa, Fla.
27. Tulsa, Okla.

At that time 4 computers were being installed and an additional 156 were on order.

As instrument landing systems, high-intensity approach-light systems with sequenced-flashing lights, and high-intensity runway-edge lights were installed, there was an increasing demand for RVR systems with a goal of installing an RVR system on every full instrumented runway.

The years following these developments have been evolutionary with no significant changes in operational principles. The RVR minimums were lowered as confidence in the RVR system increased with experience and as improvements were made in the electronic aids and lighting systems. The transmissometer baseline was shortened to 250 feet on runways intended for Category III service to permit measurements of RVR down to 600 feet [123, 26]. The computer was redesigned to provide for displaying RVR as low as 600 feet and modernized by using modern solid-state techniques. At some airports, the computers were replaced with AMOSV (automatic meteorological observation station, Mark V) which could free four computers. As the RVR minimum was reduced, better information of visibility conditions along the runway beyond the touchdown zone became necessary, and transmissometers were installed at the midpoint of some runways [113a]. Calibrators designed to replace the visual estimates used in adjusting the full scale (perfectly clear weather) reading of the transmissometer were developed and are now coming into service [29, 75].

However, the basic transmissometer, the contrast and illuminance thresholds, the illuminance level for transition from day to night scales, and the reporting increments have not been changed since the first use of the RVR system, nearly 20 years ago.

3.10 THE DEVELOPMENT AND APPLICATION OF THE RVR CONCEPT OUTSIDE THE UNITED STATES

3.10.1 European Practice:-

In Europe, the development and application of the runway visual range concept was quite different from that in the United States, in that the assessment of RVR was based entirely upon visual observations and the test period was very short. By 1953, France, Italy, the Netherlands, and the United Kingdom were using RVR operationally when the meteorological visibility was below 1200 meters (1200 yards in the United Kingdom) and Ireland was using RVR experimentally.

The practice of reporting meteorological visibility at night as the distance a black object would be seen by day, see definition 2.3.13, was an important factor in accelerating the use of RVR in Europe. At night the RVR would be roughly three times the meteorological visibility. Hence, reported visibility had little meaning.

In this period the distinction between the concepts of runway visual range and runway visibility was not clear. For example, at LeBourget the meteorological office was located 1000 feet from the end of the instrument runway and visibility was determined by observing available lights along the runway and airport boundaries. (Specific data are not available, but it is believed that the intensity of these lights in the direction of the meteorological observer was considerably lower than the intensity in the direction of the pilot.)

3.10.2 Development of RVR in the United Kingdom:-

In the United Kingdom, development of the RVR concept was stimulated by the advent of the Comet Airliner and, as in the United States, the Berlin airlift. Operational use of RVR was started at London airport following an accident in fog and the subsequent issuance of the Brabazon Report.

Operational use of RVR assessments started at Heathrow Airport in the fall of 1951. Observations were made by an observer located near the approach end of the runway in a "runway control caravan". The observer's eye height was approximately 15 feet, and he was about 120 feet from the runway edge. The observers were selected from members of the rescue and fire-fighting services and changed at hourly intervals to maintain the efficiency of observations.

> *Frequently it has been stated that this procedure involves no labor costs. Although there is no direct cost, there is a very important hidden cost in that during periods of low visibility the number of persons immediately available for fire and rescue service is reduced by two, one person observing and one in transit.*

Instrument runways were equipped with frangible pup-tent targets for day use. The targets were located beyond the far side of the runway and spaced so that the increment in distance between the observer and the targets was 100 yeards. The targets were six feet long and three feet high painted half black and half white. (Thus by day the U.K. RVR was equivalent to the U.S. RVV.)

Special gooseneck flares having an intensity of about 800 candelas were installed near the line of targets for use at night as reference lights. A rather circuitous calibration procedure was used to determine the proper distance between the observer and successive lights. These distances were chosen so that when light number "n" was at the limit of visibility, the RVR was n hundred years. In making this calibration, the average, or representative, intensity of the runway lights was not used. Instead the intensity of the runway light in the direction at which a pilot about 15 feet above the runway centerline would view the light when it was at a distance of n hundred yards was used.

The use of these end-of-runway assessments of RVR so reduced pilot complaints that the Meteorological Office felt that the need for slant visibility assessments no longer existed. (However, as will be discussed later, others in the U.K. did not agree.)

Use of this method of assessing RVR was extended rapidly to other airports. Often lights other than the "gooseneck" flares" were used as reference lights. When the runway edge lights could be seen and counted by the observer, they were used. In all cases, the observed visual range of the lights was converted to an RVR based upon runway centerline lights when such lights are installed, otherwise it was based upon the edge lights.

By 1964 the United Kingdom had found it necessary to develop a form of automatic data-transfer equipment to pass changes in RVR instantaneously as they occur and to provide air traffic controllers, notably the precision approach controller, with an illuminated visual presentation of up-to-date RVR values so that pilots may have the latest RVR value down to touchdown. The RVR value, as determined by the observer from the conversion table, was dialed to the approach and aerodrome controller's positions where the required figures appeared on an illumination indicator. Only a few seconds elapsed between the time the observation was made to the time the RVR was passed to the pilot. A simpler form of this equipment was used at some airports. The observer telephoned his count of lights to air traffic control, where the observation was converted into RVR, and the value was indicated mechanically in a master recorder and automatically relayed to slave repeaters at the various controllers positions. The time delay with this system did not exceed 30 seconds. In both systems a flashing red light indicated changes in RVR.

At the present time, the U.K. is in a state of transition with regard to the method of RVR assessment. Instrumented RVR systems have replaced or are scheduled to replace visual RVR methods at Heathrow, Gatwick, Glasgow, Liverpool, Belfast, and Edinburgh.

3.10.3 Advantages and Disadvantages of the Visual Method of Assessing RVR:-

Among the advantages of the visual method, as stated by its proponents, are:

a. Automatic compensation for the change in illuminance threshold produced by the change in background luminance, particularly during twilight.

b. A baseline longer than that of a transmissometer.

However, there are several serious disadvantages which the proponents of the visual method may have overlooked. Among these are the following:

a. The absence of continuous observations in the touchdown zone area. Hence, especially at night, it is possible for an undetected fog patch to move in over the approach and touchdown zone. The increased activity at meteorological stations during periods of low visibility, when RVR observations are most critical, precludes the use of trained personnel for runway duty as observers unless the meteorological staff is increased. The resulting use of non-meteorological personnel as observers has a number of problems associated with it. Delays are incurred in transporting people to the runway observing sites.

b. There are problems in making the observations themselves. Runway lights are difficult to count at night because they appear to merge at distances more than about 3000 feet. The intensity of the runway edge lights in the direction of the observer is frequently very different from that in the direction of the pilot, particularly at the shorter viewing distances. Hence, installation of special lights may be required.

c. The visual method tacitly assumes that the observer's threshold is equal to the pilot's threshold. (See Section 4.6).

d. Usually no allowance is made for light losses in the windscreen.

e. There are no checks on the reliability and accuracy of the data supplied by an isolated unsupervised observer.

f. Experience has indicated that changes and trends in the output of an instrument are detected earlier than from visual observations.

g. Cost of special observers and installations.

All of the factors listed above were considered by the United States in making their decision to use an instrumental method. However, despite these disadvantages, the use of visual observations is still extensive.

3.10.4 Development of Instrumental Methods:-

Despite the extensive use of visual observations, studies of the use of instruments have been conducted in many European countries including Great Britain. The feasibility of using television, automatic light-counting instruments and transmissometers has been investigated. By 1962, the United States, Canada, and the Union of South Africa were using transmissometers operationally. Australia, Denmark, France, Netherlands, Norway, and Switzerland were using them experimentally; Belgium was experimenting with television; and Germany was testing the feasibility of using a photoelectric light-counting device.

A detailed report of the status in 1962 of the application of the runway visual range and the slant visual range concepts throughout the world is given in the report of the 1963 MET/OPS meeting [70].

3.11 ICAO ACTIONS ON RVR

Note: Only those actions of the ICAO Conference, Divisions and Panels which were considered to have produced significant forward steps in the development and application of the runway visual range concept are included in this Section of the report. General discussions and reports of current practices, details of reporting procedures, etc., *have not been included. In this Section the ICAO (English) spelling of such terms such as meter, center, and color has been retained in direct quotations in which these spellings are used.*

3.11.1 The Initial Phase:-

The Brabazon Report, issued in the United Kingdom in early 1951, not only advocated operational use of the runway visual range concept in the United Kingdom but also suggested that Contracting States to ICAO should be "invited to take parallel action". This was done and the application of runway visual range measurements was considered at the First Air Navigation Conference (1954).

The First Air Navigation Conference (1954) developed a statement of operational requirements for more detailed information on meteorological phenomena which included the concepts of runway visual range and slant visual range. It was noted that some States were currently making and reporting runway visual range operationally or on an experimental basis but that there were no existing facilities or procedures for making slant visual range measurements. The Conference recognized that proposals for standardization were premature and recommended that States submit information on methods for measuring runway visual range currently being used or being investigated [60].

The Conference recommended continued investigation on methods of measuring slant visual range. The Conference also recommended that States which are not already doing so should provide, as soon as practicable, runway visual range observations and reports, at least for instrument runways, at international aerodromes when low visibility conditions exist and where justified by economic, meteorological, operational and other factors.

3.11.2 Definition of RVR:-

The following definition of runway visual range was proposed by the First Air Navigation Conference [60] for further consideration:

"<u>Runway Visual Range</u> - The maximum distance along a runway or landing strip, measured in the direction of landing or take-off from the end from which an aircraft will approach or from which it will commence its take-off run, at which the runway, landing strip or the markers or lights delineating it, are visible.

"Note 1. The use of the word "end" in this definition is not intended to limit the location of the point from which the observations will be made to the physical end (or beginning) of a runway, but observations may be made from the touchdown point, the ILS reference point, or such other points as may be agreed as most suitable to provide the most representative observations.

"Note 2. Information given on any particular occasion should be related to the objects which will be used by pilots on that occasion visually to determine their position relative to the runway."

The Second Air Navigation Conference (1955), in response to a recommendation of the International Federal of Airline Pilots Associations, agreed that RVR reports should be transmitted to aircraft en route when there were indications that the horizontal visibility along the runway was of the order of 1500 meters or less.

This definition of runway visual range, with the exception of Note 2, was included in PANS-MET 1961.

At the 1964 Meteorology and Operations Division Meeting [69], the definition of runway visual range was modified to take into account the experience which had been gained in the reporting of RVR as follows:

"Runway visual range - The maximum distance in the direction of take-off or landing at which the runway or the specified lights or markers delineating it can be seen from a specified point above its centre line from a height corresponding to the average eye-level of pilots at touchdown.

Note. - A height of 5 metres is regarded as a satisfactory approximation to the average eye-level of pilots at touchdown.

At its third meeting (1964), the Visual Aids Panel [65] found that when the fog densities corresponding to the Operational Categories (I, II, IIIa, b and c) are defined by runway visual ranges, it is not possible to specify light intensities and distributions according to category since changing the intensity changes the visual range. A note was added to the definition of runway visual range stating "For the purposes of the specifications in Annex 14 the specified lights are considered to be high intensity lights of the order of 10,000 candelas. Markers are not taken into account".

Later, at the third meeting of the All Weather Operations Panel, [57] a Note was added stating "In practice runway visual range cannot be measured directly from the position specified in the definition but is an assessment of what a pilot would see from that position".

The definition of runway visual range was revised at the Eighth Air Navigation Conference [62] to read:

> "Runway visual range is the range over which the pilot of an aircraft on the centre line of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line.
>
> "Note 1. - The height of approximately 5 metres (16 feet) is regarded as corresponding to the average eye level of a pilot in an aircraft on the centre line of a runway.
>
> "Note 2. - In practice, runway visual range cannot be measured directly from the position specified in the definition but is an assessment of what a pilot would see from that position."
>
> *Note: Until the time of the 8th ANC, as the definition of runway visual range was "refined", it became a detailed description of the procedure developed by the United Kingdom. Little or no attention was given to the operational application of the RVR concept. The definition recommended by the 8th ANC resolves the question as to whether RVR related to the pilot or the observer.*

3.11.3 Standardization of the Operational Application of the RVR Concept:-

At its first meeting (1960) the Visual Aids Panel [63] agreed that an international standard on the assessment of runway visual range was required to ensure the comparability of RVR reports and that a statement of operational requirements was required to cover such factors as the location and length of section of the runway over which RVR should be measured, whether lights, objects, or both should be used as references, and the degree of misalignment from the runway centerline that should be allowed, etc.

3.11.3.1 Location:-

Accordingly, "Runway Visual Range Measurement" was an item on the agenda of the Second Meeting of the Visual Aids Panel [64]. The panel recommended:

1. "That runway visual range (RVR) reports be made available for operational use:

   a) for landing purposes on all precision approach runways intended for use in poor visibility;

   b) for take-off purposes on all runways having high intensity edge lighting and/or runway centreline lighting, and intended for use in poor visibility;

   c) for such other runways as may be agreed locally."

2. "That, pending establishment of standard locations for RVR observations, States should:

   a) for landing purposes select a location adjacent to the runway in the first 300 metres from the threshold and, if practicable, arrange for supplementary observations from other points so as to extend, to at least 1000 metres from the threshold, the sector of the runway over which the RVR can be assessed when in the lower operational ranges;

   b) for take-off purposes, if practicable, establish observation sites different from those provided for landing purposes, by selecting one or more locations which will provide an indication of the RVR over the last 1000 metres of the average take-off role of the more critical of the civil transport aircraft regularly using the runway."

3. "That states working on RVR observation procedures be invited:

   a) to modify their programs where practicable, with a view to providing information on aspects of RVR observing and reporting that need further study before the subject is considered at the MET/OPS Meeting (1963) ----."

Using the material obtained as a consequence of recommendation 3, the 1964 Meteorology and Operational Divisional Meeting [69] implemented the first recommendations with the following,

"Runway visual range observations shall be made at aerodromes, for inclusion in reports issued in accordance with 2.2.1, 2.2.2 and 2.2.3, throughout any operationally significant period during which the horizontal visibility is equal to or less than a value - not below 1,000 m - specified by regional air navigation agreement, on runways intended for use during such periods of reduced visibility and selected as follows:

a) precision approach runways;

b) runways used for take-offs and having high intensity edge lighting and/or centre line lighting;

NOTE: Local arrangements should be made to allow the runway visual range reporting system to be brought into operation quickly, especially when a rapid deterioration in visibility occurs or is expected."

(The NOTE is indicative of the difficulties encountered in staffing an RVR observation post when RVR is based upon reports of a human observer. In the U.S., transmissometers have been operated 24 hours a day, 7 days a week from the beginning of their use.)

In response to the recommendation of the Visual Aids Panel concerning location of the RVR observations, the MET/OPS meeting (1964) "agreed that the requirement for landing was for a report on the visual range from a location 300 m along the runway from the threshold supplemented by information up to 1,500 m from the threshold. For take-off, there was a requirement for additional information for the latter parts of the take-off role. It appeared that these requirements would be satisfied by observations along the runway about 300 m from the threshold together with observations at about the mid-point of the runway or at a location about 300 m from the other threshold of the runway. However, it was decided that it would be best to be specified only regarding the need for observations at about 300 m from the threshold, leaving the location of other observation points to be determined locally in a way that would best suit local conditions, e.g., if there were a swamp near one part of the runway a special observation point in this area might be found desirable. It was also considered necessary to provide pilots with an indication of the significant variations with time."

3.11.3.2 Observational Techniques

None of the ICAO Panels, Divisions, and Conferences has considered it advisable to introduce complete standardization into the methods of assessing runway visual range, considering that both visual observations and instrument measurements had been in use from the start of operational application of the RVR concept. It was recognized that either method, carefully employed, was adequate to meet the operational needs. In the early 1950's there was a strong bias for visual observations but recently the trend has been toward the use of instruments.

3.11.3.3 Reporting of RVR

Reporting Increments

The 1964 MET/OPS Divisional Meeting recommended that observed values of RVR up to 500 meters (1600 feet) be reported insofar as possible in steps of not greater than 50 meters (160 feet), those from 500 to 1000 meters (1600 to 3200 feet) in steps of not greater than 100 meters (320 feet) and those above 1000 meters in steps not greater than 200 meters (700 feet).

However, later in the year, the All Weather Operations Panel at its First Meeting (1964) [55] did not agree and recommended instead that

RVR should be reported in increments of 30 meters without stating the range of RVR measurements to which the recommendation was applicable. At its Second Meeting (1967) [56] the Panel clarified the recommendation stating that it applied to Categories II and III only and recommended that RVR values be reported in increments as follows:

OPERATIONS	REPORTING INCREMENTS
Category I	Specifications recommended by the MET/OPS Meeting (1964) given in preceding paragraph satisfactory.
Category II	30 m (100 ft)
Category III	30 m (100 ft)

NOTE: Until improved techniques are available to allow this, reporting increments of the order of 50 m (160 ft) or 60 m (200 ft) would be acceptable for the RVR in CAT II operations. To achieve the limit of CAT IIIB, additional refinement in RVR or visibility measurements will be needed.

The Panel also considered the procedure for issuing Special Reports and found that for Category II and III operations "the system of routine and special reports was not suitable as a means of keeping the appropriate ATS unit informed regarding the current RVR, and that the service should be virtually continuous and subject to negligible delay - at least while the aircraft was on final approach. The Panel also believed that it would be most helpful to supplement the reports by very short period forecasts if these could be given with sufficient accuracy."

The Panel accordingly recommended "that for aircraft for which the applicable RVR minimum for landing on the runway to be used is 800 meters (2600 ft) or less, the following procedure be used for keeping the appropriate ATS unit informed of the current RVR value and its expected changes from the time final approach is commenced until the landing is completed:

a) the runway visual range should be reported to the appropriate ATS unit within 15 seconds whenever there is a change in the value to be reported in accordance with the reporting scale in use, provided that the RVR before or after the change is 800 metres (2600 ft) or less; the integrity of the communication link should be assured;

b) when practicable a forecast of RVR for the ensuing 10 minutes, expressed as a trend (e.g., decreasing rapidly), should be added to each report and should be corrected whenever appropriate."

This recommendation was further modified by the All Weather Operations Panel at its Third Meeting (1967) [57] to authorize the use of 60 meter increments for observed runway visual ranges in the upper region of Category II operations (500 meters to 800 meters), and at the Eighth Air Navigation Conference provision was made for reporting RVR in increments of 25 to 60 meters at the low end of the scale and 100 meters was recommended for RVRs above 800 meters [62].

The Upper Limit of RVR

The First Air Navigation Conference (1953) was of the opinion that reporting of runway visual range should commence when the horizontal (meteorological) visibility fell, or was expected soon to fall, below 1000 meters or a higher figure as agreed locally [60]. This figure was formally recommended by the MET/OPS Divisonal Meeting in 1964 although the International Federation of Airline Pilot Associations had recommended that observations start when the meteorological visibility fell below 1500 meters.

The Fifth Air Navigation Conference (1967) [61] accepted the 1500 meter limit in order to provide more adequately for operations in the lower visibility ranges of Category I. It was recognized that under some conditions in which the visibility was 1500 meters, or somewhat lower, the RVR would exceed the upper limit of the system in use, whether instrumental or visual, recommending that when the visibility is below 1500 meters and the RVR is above 2000 meters, RVR may be reported as RVR above 2000 meters. The upper limit of 2000 meters was reduced to 1500 meters by the Eighth Air Navigation Conference [62].

This latter change is in accord with U. S. Practice of reporting RVR values above 6000 feet (1800 meters) as 6000+.

Rounding Down of RVR Values

The Fifth Air Navigation Conference also recommended that RVR values should be rounded down to the nearest incremental value of the reporting scale in use.

> *This recommendation is in conflict with U. S. Practice in that when transmittance measurements are converted to RVR values the value reported is the RVR corresponding to the transmittance at the midpoint of the transmittance increment. Thus, at night, transmittances, over a 250-foot baseline, in the range 0.030 (RVR of 500 feet) to 0.104 (RVR of 700 feet) are reported as an RVR of 600 feet.*

Pilot Eye Height

Throughout the course of the development of the operational application of the RVR concept in ICAO, a pilot eye height of 5 meters has been assumed as being representative of the average eye height at touchdown. This is in accord with the technique used in 1951 by the United Kingdom and others using visual observations. In the United States and in other States using the U. S. transmissometer, the receiver and light source are installed at a height of approximately 15 feet thus representing the average height, at touchdown, of the line of sight from an aircraft with a pilot eye height of 30 feet.

The advent of "jumbo" and supersonic aircraft with pilot eye heights at touchdown of 30 feet, or more, has reopened the question of instrument mounting height. Sufficient data are not available to date to resolve the question as to whether:

a) the present RVR values, related to an average eye level of 5 meters, are sufficient; <u>or</u>

b) RVR values relating to a compromise pilot eye level for all aircraft could or should be provided; <u>or</u>

c) two values of RVR, one related to an eye level of 5 meters and one to some higher eye level, say 15 meters, could or should be provided.

Choice of Light Targets

Under some visibility conditions the runway edge lights provide better guidance than do the runway centerline lights. In very low visibility conditions the centerline lights provide the primary guidance. The ideal system should allow for usage of either. However in the beginning, some States, including the United Kingdom, used an RVR system based upon centerline lights only, and others, including the United States, based their RVR system on edge lights only. The question of the proper selection was complicated by such factors as the low intensity of many centerline lighting systems, the additive effects of the centerline lights under many conditions of view, and the narrow horizontal beam spread of many edge lighting systems. Several solutions were proposed over the years. Then, in 1974, the 8th Air Navigation Conference [62] resolved the issue by accepting the recommendation of the Fourth Meeting of the All Weather Operations Panel [58] and prepared the following guidance material.

"GUIDANCE MATERIAL ON LIGHTS TO BE USED FOR ASSESSMENT OF RVR

"The following guidance material is necessarily general in nature, since it is recognized that there can be a wide variance in individual lighting configurations and light characteristics. The major concern is that there be the greatest degree of standardization possible, so that RVR readings will give uniform results worldwide and it is the function of States to ensure that RVR values are as representative as possible of actual visibility conditions:

a) For runways on which the centre line and edge lights conform to the specifications for Precision Approach Runways, given in Annex 14, Table V-1, RVR measurements should be based on the edge lights, since these lights give a representative indication of the visual guidance provided by the whole system.

b) For runways on which the centre line and edge lights do not conform to the specification s referred to in a) above, RVR reports should be based on one or both sets of lights over certain ranges of values determined as follows, where R_C is the

RVR based on centre line lights and R_E is that based on edge lights:

1) RVR should normally be determined as R_C for values of R_C up to about 350 metres (1,150 feet).

NOTE: An upper limit for R_C between 300 and 350 metres (1,000 and 1,150 feet) may be satisfactory where the guidance provided by the edge lights is abnormally high compared with that provided by the center line lights (e.g., because of unusual relative intensites or beam spreads). An upper limit above 350 metres (1,150 feet) may be satisfactory where the opposite is the case (e.g., where the edge lights have unusually wide lateral spacing or the center line lights have unusually favourable characteristics).

2) RVR should be determined as R_E for values of R_E more than about 250 metres (820 feet) above the upper limit for RC.

Note: The lower limit for R_E may need to be raised in a few cases to avoid having in the transition zone, too rapid a change in RVR with meteorological visibility or with the atmospheric transmission factor for the transmissometer baseline.

3) The transition from the upper limit of R_C to the lower limit of R_E should be approximately linear between the corresponding points on graphs of R_C and R_E versus meteorological visibility or atmospheric transmission factor for the transmissometer baseline."

Sampling Period

The problem of the length of the sampling period (the length of time over which transmittance is averaged for the determination of an RVR value) did not arise until the trend to replace the visual observation with an instrumental measurement was established. At its Third Meeting, the All Weather Operations Panel [57] considered the problem and noted that in order to obtain a representative RVR reading based upon the transmittance over a transmissometer baseline, the sample had to be taken over a sufficient period. However, in order to obtain an indication of sudden changes, the sampling period should be kept as short as possible and in no case should exceed 60 seconds.

Throughout the development of instrumental methods of assessing RVR, there were many who believed that the requirement for a sampling period of the order of 60 seconds was an indication of a deficiency in the instrument and did not realize that the requirement was not a limitation of the instrument but was based primarily upon meteorological considerations. Hence, a minimum length of sampling period was not stated until, in 1974, the 8th Air Navigation Conference recommended that the sampling period be not less than 30 seconds.

Standardization of Intensities and Thresholds Used in the Assessment of RVR

a. Intensities

The All Weather Operations Panel at its Third Meeting (1967) found that "since RVR is the distance at which a particular light may be seen in given circumstances, the same opacity of the atmosphere may represent different values of runway visual range due to different light intensities. The Panel, however, recognized that there was some relationship between RVR and the probability of being contact at a given height. They therefore saw an advantage in standardized runway and approach lighting intensities so that the same numerical values of RVR would mean the same horizontal thickness of fog and in many cases the same chances of approach success. Such standardization would also improve the comparability of RVR observations made on different runways and at different aerodromes, - for example, by reducing variations in the allowance to be made for exposure to approach lighting in determining the value of pilot visual threshold to be used in computing RVR." The Panel recommended that the Visual Aids Panel consider "the advantages, in regard to both the observation and the interpretation of RVR, that would result from standardization of the relative intensities of runway and approach lighting."

These factors were considered by the Visual Aids Panel at its Fifth Meeting (1970) [67]. The Panel noted that "RVR is a function not only of the intensity of the lights used to determine RVR but also of the setting of the intensity control of the system and of the visual threshold assumed for the pilot (and for the observer when visual observations are used for the determination of RVR)." The Panel agreed that RVR values should be based upon an intensity representative of the performance of a light in service and prepared the following statement:

> "RVR intensity: The intensity to be used in the assessment of RVR is the intensity of a typical new light averaged over the beam spread specified in Table V-1 with all intensities greater than three times the minimum intensity within this region considered

as being only three times the minimum. The RVR intensity is equal to the average intensity so computed multiplied by an appropriate reduction factor. The reduction factor should account for the decrease in intensity caused by lamp blackening and contamination of the optical surfaces. This factor is dependent upon such details as the type of light, elevated or inset; the location of the lights; and the established maintenance programme. Factors ranging from 0.8 for runway edge lights to 0.5 for runway center line lights were suggested.

"The Panel considered specification of minimum and maximum intensities for approach and runway lights undesirable since uniformity within the beam of individual lights had been specified; since compatibility between approach and runway lights had been obtained by specifying the ratios of their intensities; and since there can be no fixed relation between fog density and RVR as presently defined if the intensity of the lights is adjustable. However, a relation between RVR and the probability of being contact at a given height had been obtained. Further study of contamination reduction factors and of the additive intensity effect of closely spaced runway centre line lights was required."

Throughout the course of its development RVR has been considered in two ways: a) As defined, it is the maximum distance at which a pilot in a specified location would be expected to see the particular lights used in a specified system; and b) as a measure of the fog density, similar to meteorological visibility, expressed in a distance approximating the visual range of approach and runway edge lights.

Both concepts are sometimes expressed in the same paragraph, as in the AWOP recommendations quoted above.

If the first concept is accepted, the intensity used in assessing RVR would be the intensity emitted by a typical light in the direction of the pilot. Since the intensity *changes with the distance from which the light can be viewed, the intensity in the direction of the pilot is different from each runway light. Hence, a different intensity would be required for each value of RVR. The conversion charts used by the U.K. to obtain RVR from visual observations followed this practice. The Fifth Air Navigation Conference agreed with the first concept and recommended that account be taken of the variation of intensity with angle of view and also of the intensity setting in use for the lights.*

If the second concept is accepted, intensity representative of the intensity of approach and runway lights over an angular region covering the expected approach path of the aircraft would be used. This concept is most effective when the representative intensities of approach and runway lights do not differ significantly. This second concept is the one used by the Visual Aids Panel in preparing its material and is in accord with U.S. practice.

Since the intensities of both the runway and approach lights are adjusted, often independently, to accommodate the systems to fog density and background luminance, there will not be a fixed relation between RVR and fog density, or approach success as desired by the All Weather Operations Panel, unless intensity control as well as design intensity is standardized.

b. Thresholds

When visual observations are used in assessing RVR the question of illuminance threshold does not arise since it is assumed that the pilot's and observer's thresholds are equal. However, knowledge of illuminance threshold is required when RVR is assessed from instrumental measurements, as is evident from equation (2.15). In order to obtain a fixed relation between RVR and horizontal fog density, the values of illuminance threshold used in obtaining RVR from transmittance measurements must be standardized.

This question was considered at the Third Meeting of the All Weather Operations Panel [57] which recommended, on an interim basis, the use of the illuminance thresholds used by the U.S., 1000 mile candles (3.9×10^{-4} lux) by day and 2 mile candles (7.7×10^{-7} lux) by night with the change between day and night occurring at a horizontal background illuminance of 2 footcandles (22 lux). The Panel also believed that 0.05 was a suitable value for the contrast threshold when markings rather than lights were used for guidance.

However, at the time the recommendation for illuminance thresholds was made, one State was using a four-step illuminance threshold system and another was making measurements of background luminance at the time of each transmittance measurement and using a continuous adjustment of illuminance threshold. At its Fourth Meeting, the All Weather Operations Panel [58] revised its opinion and prepared the following guidance material:

> "The following constants are given for guidance for use when converting transmissometer indications into runway visual range:
>
> Pilot contrast threshold - 0.05 (dimensionless)

	Illumination Threshold (lux)	Illumination Threshold (Mile Candles)	Background Luminance (cd/m^2)
Night	8×10^{-7} or $10^{-6.1}$	2	4-50
Intermediate Value	10^{-5}	26	51-999
Normal day	10^{-4}	260	1000-12000
Bright day (e.g., sunlit fog)	10^{-3}	2600	more than 12000

> "The above values are given in the interest of obtaining standardization of RVR readings. The four illuminance thresholds are equally spaced and are convenient in converting values of transmission factor (transmittance) to RVR. However, other intermediate and normal day threshold values may be used provided

they give more conservative (lower) values of RVR which are proven to be operationally acceptable.

"The above illumination threshold/background luminance relationship is shown diagrammatically below* in the form of a step function. When, in the computation of RVR, the illumination threshold is adjusted continuously in accordance with the output of a background luminance sensor values derived from the continuous threshold/background luminance relation curve shown in the diagram should be used.

"The number of illumination threshold values to be used at any location will depend on the frequency of occurrence and duration of various levels of background luminance. For example, in some areas two values may be found adequate."

In addition States were invited to continue their studies of illumination thresholds.

The authors are convinced that the threshold values proposed above are not appropriate. See Sections 4.4.8 and 7.4.6.

*Not included in this report.

4. THEORY OF VISUAL RANGE

4.1 VISUAL RANGE OF OBJECTS

An object will be seen against a sky or terrestrial background if the apparent contrast (see Section 2.1.12) between the object and its background is above some minimum value. This apparent contrast is reduced by the scattering action of the air molecules and aerosols in the line of sight between the observer and the object. The purpose of this section is to study the effects of the atmosphere on the visual range of objects.

4.1.1 Historical

Although the development of the visual range of objects is usually attributed to Koschmieder, Middleton [93] has shown that Bouguer in 1758 developed a sound theory of the reduction in contrast between a dark object and a sky background. The principles were rediscovered by Lambert a few years later. Since there was no immediate application for this knowledge, the study of the visibility of objects was essentially dormant until the advent of aviation.

4.1.2 Objects with Sky Background

In 1924, on the assumption of a uniform atmosphere having a scattering coefficient β, and illumination by the sun and a uniform sky (overcast or cloudless), Koschmieder [78, 79] showed that the light scattered into the line of sight by the air molecules and aerosols is such that the apparent luminance, L_x, of a black object at a distance x, viewed against the horizon sky is

$$L_x = L_h(1 - e^{-\beta x}), \qquad (4.01)$$

where L_h is the luminance of the horizon sky in the direction of view, and β is the scattering coefficient.

The apparent contrast C_x of the object and the horizon sky is then

$$C_x = (L_x - L_h)/L_h. \tag{4.02}$$

Thus,

$$C_x = -e^{-\beta x}. \tag{4.03}$$

If an observer recedes from a black object with the sky behind it, the apparent contrast C_x decreases according to equation (4.03), until at some distance R it becomes numerically equal to ε, the contrast threshold. This distance R is the visual range, V. Therefore,

$$\varepsilon = e^{-\beta V} . \tag{4.04}$$

Koschmieder also showed that if the inherent luminance of the object is not zero, (4.01) may be generalized to

$$L_x = L_o\ e^{-\beta x} + L_h(1 - e^{-\beta x}) . \tag{4.05}$$

This is the basic relation in the theory of the visual range of objects and all later work evolves from it,

The first term of (4.05) represents the direct attenuation of the intrinsic luminance of the object by scattering due to the fog droplets. The second term represents the additional contribution to the apparent luminance of the object due to "airlight" or external illumination from all directions which is scattered into the observers eye by the fog droplets.

The foregoing equations contain no mention of absorption, which in reality is sometimes as important as scattering. Absorption could easily be accounted for by simply substituting σ for β in the foregoing equations, although it is not immediately obvious how such an extension can be justified. Later work by Duntley [31] and others has justified this change and (4.05) may be written as

$$L_x = L_o\ e^{-\sigma x} + L_h(1 - e^{-\sigma x}) . \tag{4.06}$$

Similarly, (4.04) may be written

$$\varepsilon = e^{-\sigma V}, \tag{4.07}$$

and, since the transmissivity T is equal to $e^{-\sigma}$, (see Section 2.2.7)

$$\varepsilon = T^V. \tag{4.08}$$

Equations (4.07) and (4.08) are generally referred to as "Koschmieder's Law".

Koschmieder assumed a value of 0.02 for ε. Later work indicates that the contrast threshold is higher than this, and the World Meteorological Organization recommends a value of 0.05. Contrast thresholds are discussed in detail in Section 4.2.

Combining (4.02) and (4.06) yields

$$C_x = [(L_o - L_h)/L_h] \, e^{-\sigma x}.$$

Since

$$C = (L_o - L_h)/L_h \quad , \tag{4.09a}$$

$$C_x = C_o \, e^{-\sigma x} \quad , \tag{4.09b}$$

or

$$C_x = C_o \, T^x. \tag{4.09c}$$

If the object is just visible,

$$\varepsilon = C_o \, e^{-\sigma V} \qquad (C_o > \varepsilon), \tag{4.10a}$$

or

$$\varepsilon = C_o \, T^V \qquad (C_o > \varepsilon). \tag{4.10b}$$

Solving for V,

$$V = (\ln C_o - \ln \varepsilon)/\sigma \; , \tag{4.11a}$$

or

$$V = -(\ln C_o - \ln \varepsilon)/\ln T. \tag{4.11b}$$

Note that in equations (4.11), and in subsequent equations using the logarithms of contrast, apparent contrast, and contrast threshold, the convention of considering these terms negative when the object is darker than its background is abandoned and these terms are considered positive.

This is permissible as these terms are always of the same sign, for atmospheric scattering never reverses contrast.

It is apparent from equations (4.11) that the visual range of an object is determined by the inherent contrast of an object, C_o, the extinction coefficient, σ, (or the transmissivity, T) and the contrast threshold, ε. Methods of measuring T and σ will be discussed later (Sections 5.1 and 5.2), as will the choice of an applicable value of ε (Section 4.2). There is, however, no feasible way of determining C_o except by direct measurement of L_o and L_h. Moreover, except for black objects, C_o is not constant but will vary with the extent of cloud cover and with the position of the sun with respect to the object.

It is for these reasons that black, or very dark, objects are chosen as marks for the Weather Observer. Under this condition the value of C_o is -1, or nearly so, the logarithm of the absolute value of C_o is very close to zero, and (4.11) reduces to

$$V = (-\ln \varepsilon)/\sigma, \tag{4.12a}$$

or

$$V = (\ln \varepsilon)/\ln T \ . \tag{4.12b}$$

It is obvious that (4.12a and b) may also be obtained directly from (4.07) and (4.08).

Note that the visual range V of a black object is, as indicated by (4.12), independent of luminance of the background sky and the direction of view with respect to the sun.

Although variation in contrast is not a significant factor in determining the accuracy of routine meteorological observations, the effect of contrast on visual range is of interest because the visual range of many objects which are not black, for example, tall buildings and lighthouses, is of interest. The effect of contrast on visual range is illustrated in figure 4.1. The visibility factor, K, is the ratio of the visual range of a large object of inherent contrast C_o to the visual range of a large black object. The equation for the visibility factor is obtained as follows. Let V' be the visual range of an object of contrast C_o. Then from (4.11a),

$$V' = (\ln C_o - \ln \varepsilon)/\sigma \tag{4.13}$$

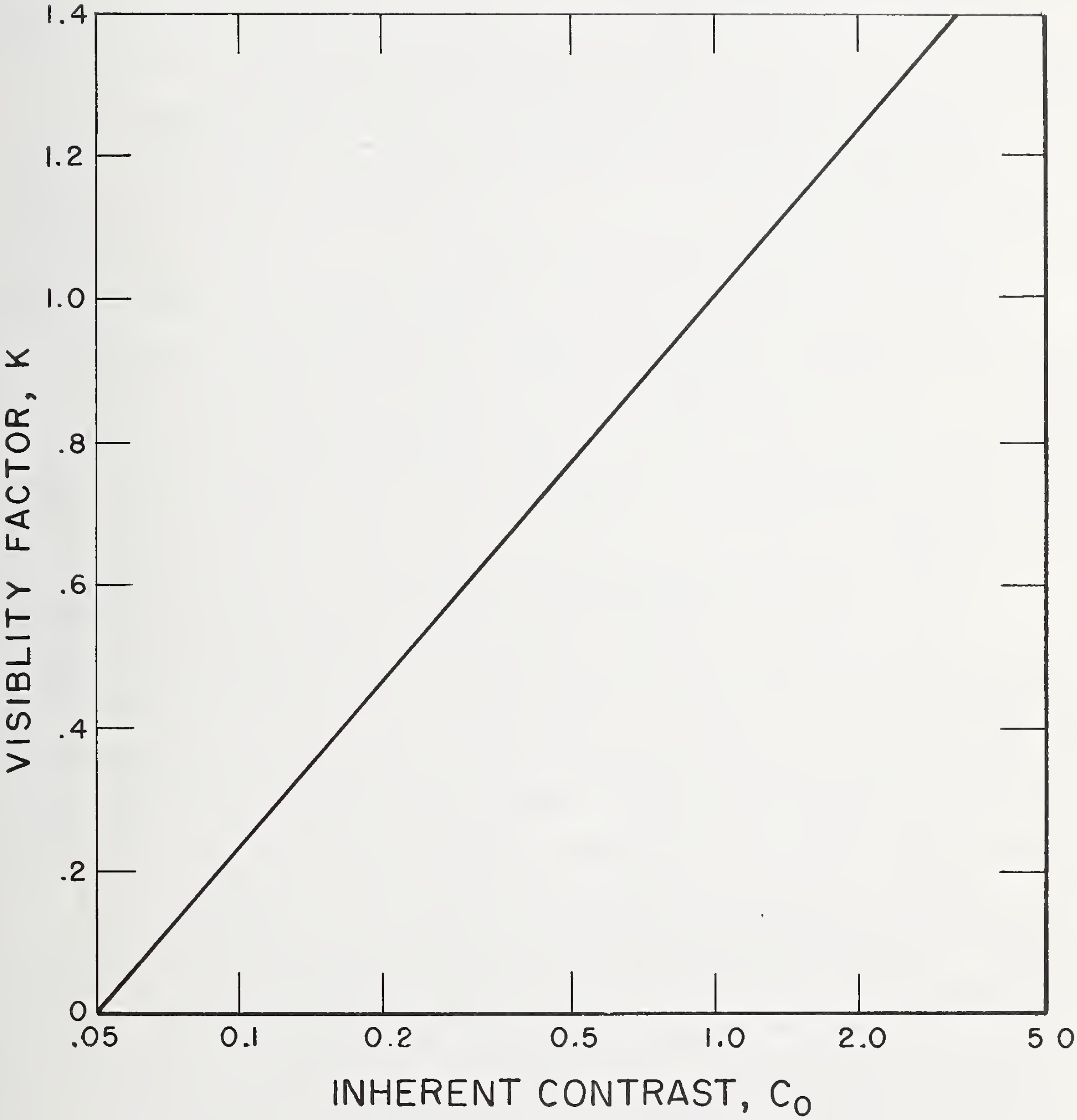


Figure 4.1 Effects of inherent contrast upon visibility factor. K = 1 when C_o = 1. A contrast threshold of 0.05 is assumed.

Dividing (4.13) by (4.12a) yields

$$K = V'/V = 1 - \ln C_o/\ln \varepsilon. \tag{4.14}$$

For reasons which will be apparent later (Section 4.2), a value of 0.05 was assumed for ε.

Values of C_o range from -1 (+1 on figure 4.1 for reasons stated above), through zero for a grey object so lighted by daylight that it blends with the sky, to as high as 5 for a white object in direct sunlight. A extensive discussion of the luminances found in nature has been prepared by Gordon [39].

4.1.3 Objects with Terrestrial Background

The apparent contrast, and hence the visual range, of an object viewed, horizontally, against a background other than the sky may be computed by applying (4.05). This has been done by Duntley [31] in a generalized treatment of slant visibility. For objects viewed against an immediate terrestrial background, such as painted stripes on a runway, the following relation applies:

$$\varepsilon = C_o[1 + (L_h/L_b)(e^{\sigma V'} - 1)]^{-1}. \tag{4.15}$$

In the foregoing relation, C_o is the inherent contrast between the mark and its background, V' is the visual range of the object, L_b is the inherent luminance of the background of the object, and L_h is the luminance of the horizon sky in the direction making the same angle at the object with the line of sight as it does with a line from the object to the sun. In this situation the apparent contrast, and therefore the distance a mark can be seen, is a function of the direction of view, the luminance of a particular section of the sky, and the inherent luminance of the background as well as the contrast between the mark and its background. When the line of sight is horizontal, L_h is the luminance of the portion of the sky directly behind the mark and its background. In the case of a landing aircraft, the line of sight is within a few degrees of the horizontal projection of the line of sight.

The visibility factor, K, obtained by combining (4.15) and (4.12a) is given by

$$K = \ln[1 - (L_b/L_h)(1 - C_o/\varepsilon)]/(\ln 1/\varepsilon). \qquad (4.16)$$

Note that K is independent of the visibility or transmittance of the atmosphere.

The results of computations of the visibility factor by means of this equation are shown in figure 4.2. A contrast threshold value of 0.05 was used in making the computations.

In considering the curves, the following information should be helpful. The ratio L_b/L_h varies from about 5 or more on a sunny day with a snow background down to less than 0.01 in directions near a low sun shining through a haze with a grass background. In the case of a grass background on an overcast day, the ratio will be about 0.2 to 0.3. On hazy days, with the sun visible through the haze, the ratio may vary over a range of more than 10 to 1 around the horizon.

The contrast between a runway and its marks or its background is usually in the range 0.5 to 2.0. Contrasts between natural objects and their backgrounds may be as low as 0.2 [20, 39]. The conditions at the upper righthand part of the figure are not common and usually require, in order to simultaneously produce both a high contrast and a high value for the ratio L_b/L_h, that sunlight be specularly reflected from the object.

In general, therefore, the visibility factor will be less than one, ranging from 0.3 to 0.6 under overcast daylight conditions to less than 0.1 with a low sun shining through haze.

The development of the theory of the visibility of objects given above has been simplified in the interest of brevity and clarity. A uniform atmosphere with a constant extinction coefficient, or transmissivity, has been assumed. The restrictions stated by those who developed the theory have not been listed. However, field experience has indicated that the equations developed above are sufficiently general to represent the visual range of objects in practical applications.

For more complete treatments see Middleton [95] and Duntley [32, 33] and the references listed therein.

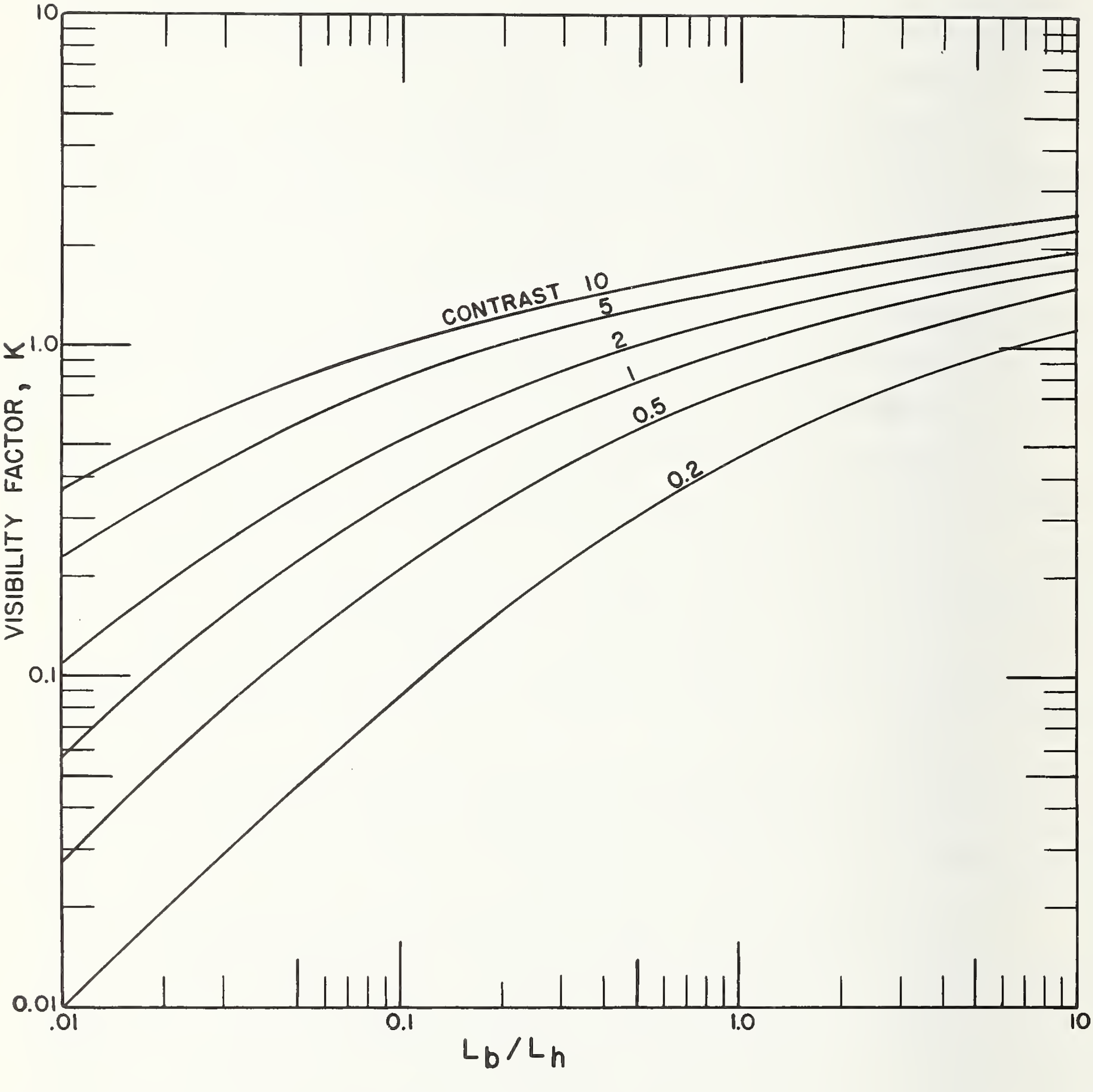


Figure 4.2 Effects of ground/horizon sky luminance ratio and contrast on visibility factor for objects with a terrestrial background, based upon a contrast threshold of 0.05.

4.2 CONTRAST THRESHOLDS

Light falling on the eye acts as a stimulus. If the stimulus is intense enough, an individual will experience a sensation; e.g., a sensation of brightness. Brightness, as a psychological concept, cannot be measured in the physical sense.* However, it is valid to make judgements as to the equality or inequality of two or more sensations. The least stimulus that will produce a sensation is known as the absolute threshold for that stimulus. Similarly, the smallest difference between two stimuli which will make their corresponding sensations distinguishable is known as a difference lumen. If two adjacent objects are just distinguishable, and the luminance of one is L_1 and the other is L_2, then

$$(L_1 - L_2)/L_2 = \Delta L/L_2 = \varepsilon. \tag{4.17}$$

which defines ε, the contrast threshold.

4.2.1 Daytime Thresholds in Practice

Koschmieder used the value of 0.02 for the threshold of contrast based upon the work of Helmholtz in photometry. There is no indication that this choice was based on any field experiment. The use of this particular value has continued for some uses and is regarded by some as the standard value for meteorological uses. Its usage gives the equation 4.12a the form

$$MR = 3.912/\sigma. \tag{4.18}$$

Also from (4.08),

$$T^{MR} = \varepsilon^{-\sigma MR} = 0.02.$$

The quantity MR is defined as the meteorological range, an unfortunate choice of words as will be seen later. The natural logarithm of ε is traditionally given to four significant figures, implying that the contrast threshold, ε, is known to an accuracy of one part in ten thousand. A value of 4 would be more appropriate.

Among the more recent laboratory studies to determine contrast threshold, those by Blackwell [9], and Lamar et al [82] are noteworthy. These researchers determined the luminance contrast under laboratory

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*Brightness is not the same as luminance. Luminance is a psychophysical concept and can indeed be physically quantified (measured).

conditions while varying size and shape of stimuli, with stimuli both lighter and darker than the background, with varying exposures.

The thresholds obtained by Blackwell and others in their laboratory experiments were lower than those obtained in field experiments. The field experiments of Houghton [49] and Douglas and Young [30] suggested a threshold of about 0.05 and led Blackwell to undertake an extensive outdoor experiment to validate the application of laboratory results fo field situations. These tests were conducted in the forest country of northern Michigan and are generally known as the Roscommon tests [10]. Blackwell checked parts of his earlier results by direct observation in the field, using distances up to 30 miles, with some of the observations with binoculars, some with the naked eye, and by night as well as in the daytime. These observations showed that the results of laboratory experiments could be applied to field observations, with a tolerance of ±25 percent, if the conditions of observation were the same, i.e., "forced-choice" response by an observer with knowledge of the exact location of the target.

These conditions are, however, not those of the meteorological observer. Although he knows the general location of the visibility marks, he needs to see them sufficiently well so that he *knows* that he is observing the desired mark. Hence he uses a recognition, not a forced-choice detection, threshold. Therefore the contrast-threshold chosen for the meteorological observer, and later for the pilot was based upon field experience such as that of Houghton [49], Douglas and Young [30], and ANDB [126], who used criteria of recognition, not detection. Later, Middleton [95] used routine meteorological observations of "the visibility" to determine a relevant contrast threshold.

In view of these studies, the World Meteorological Organization (WMO) recommends that the value of 0.05 be used for the contrast-threshold in computing visual range from measurements of fog density. Thus (4.12a) may be written

$$\mathrm{MOR} = 3/\sigma. \qquad (4.19)$$

The quantity MOR is defined as the meteorological optical range.

A value of 0.055 is used for transmissometer-based computations of visual range in the U.S., based upon work described in Sections 7.2 and 7.3.

As shown by (4.12) the visual range is a function of the logarithm of the contrast threshold and thus is not very sensitive to a change in the value of ε. For example, the ratio of the meteorological range (MR) to the meteorological optical range (MOR) is 4/3 although the ratio of the two thresholds is 2.5. The effects of changes in contrast threshold on the visibility factor are shown in Figure 4.3. The general relation is

$$V_1/V_2 = \ln \varepsilon_1/\ln \varepsilon_2 \tag{4.20}$$

where V_1 is the visual range computed from (4.12) using ε_1 as a threshold and V_2 is the visual range obtained using ε_2.

It should be noted that the above discussion tacitly assumes that the contrast-threshold, ε, is a constant when, in fact, it is a function of the angular size of the object and upon the background luminance, increasing as these parameters decrease. However, under field conditions with objects subtending 0.1 degree or more and under normal daylight conditions, the recognition contrast-threhold is sufficiently stable that assuming it to be a constant does not introduce significant errors.

4.2.2 Contrast Threshold Criteria

The difference between the contrast threshold value of 0.055 used in the transmissometer calibration and the value of 0.02 which had been traditionally used to relate meteorological observations of visibility to transmittance is due to several factors including threshold criteria. Instructions used by weather observers stated that "visibility in a definite direction is the greatest horizontal distance at which outlines of visibility markers can be distinguished against the horizon sky" [128]. This criterion was used in the initial transmissometer calibration*. The distance at which the most distant mark appeared as a square was called the visual range. Beyond this mark one, and sometimes

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*These field experiments were conducted on Nantucket Island, Mass., and are covered extensively in Chapter 7.

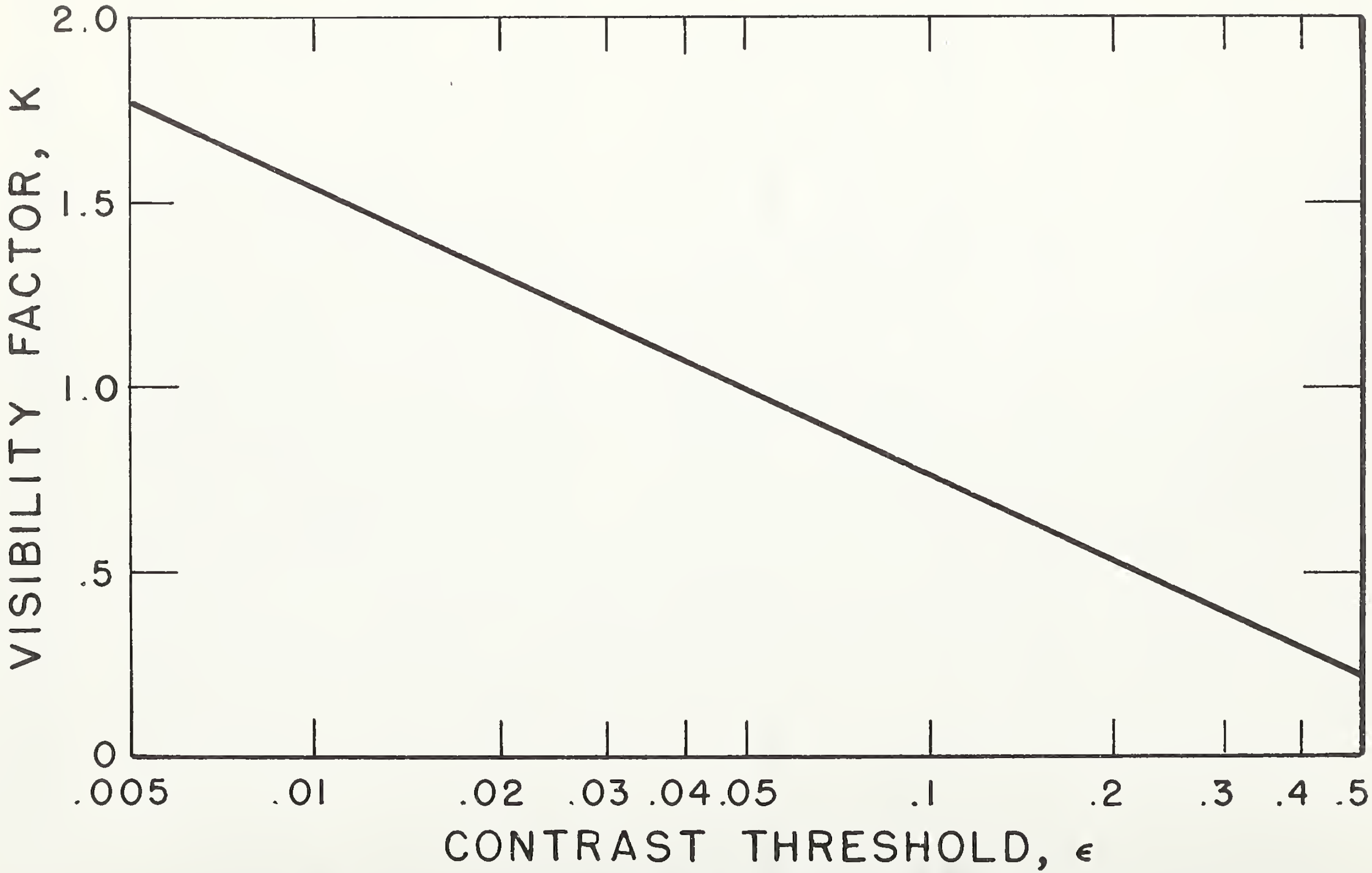

Figure 4.3 Effect of change in contrast threshold upon visibility factor, K = 1 when ε = 0.05.

two, additional marks appeared as shapeless smudges but could not be seen well enough to be identified. It is unlikely that these marks could have been located had it not been for the guidance furnished by the visible marks. Usually, contrast threshold values lower than 0.055 have been based upon experiments where the criterion of visibility was any detection of a mark whose location is known.

The recognition threshold derived for objects by day during the Nantucket field tests was determined using observers knowing the approximate location of the marks. The search time was nearly imperceptible when the marks, both objects and lights, were at the recognition threshold. Once the mark was initially located, there was no doubt on the observer's part as to its location.

During the 1940's, a qualitative study of the effect of the differences in criteria of visibility was made during the course of observations in fog at the Landing Aids Experiment Station by evaluating the distances at which an observer, knowing the location of a mark, could just detect it and the distance at which the shape of the mark could be distinguished (recognized). If ε_1 and x_1 are the contrast threshold and distance values for the detection case and ε_2 and x_2 the corresponding values for the recognition case, then

$$\varepsilon_1 = T^{x_1} , \varepsilon_2 = T^{x_2}$$

and

$$x_1/x_2 = \ln \varepsilon_1/\ln \varepsilon_2$$

which shows that the ratio of the distance is independent of the prevailing transmittance. Since the line of sight is nearly the same in both cases, the effect of any non-uniformity in the fog is considerably reduced. Therefore, the number of observations needed to determine this ratio is considerably less than the number required in determining the actual contrast threshold. The ratio, based upon 23 observations made in fogs varying in visual range from 0.06 to 1 mile, was found to be 1.09 with a coefficient of variance of 4 percent. On the basis of

0.055 as the recognition threshold and 1.09 as the ratio of the two distances, the detection threshold computed from (4.20) is 0.041.

Another factor which may account for some of the difference between laboratory and field values of contrast threshold is the difference in uniformity of background luminance. Byram [19] suggested that the detection threshold of 0.02 should be increased to a value on the order of 0.03 to 0.04 due to local variations in retinal adaptation resulting from the large point-to-point variations in background luminance of outdoor scenes.

Another factor to be considered is the size of the marks. The contrast threshold 0.02 was based upon objects subtending one degree or more. The marks used in calibrating the transmissometer were somewhat smaller than this. They were, however, about the same angular size as marks often used by meteorological observers in determining visibility, since marks even as large as 0.5 degree frequently are not available. For instance, a one degree target 5 miles away would have to be 460 feet square while a typical two story house would provide a one degree mark at a distance of less than one-half mile. Moreover, the density of fog and haze frequently varies so much from point to point that, with a mark as large as one degree, parts of it may be below the limit of visibility while other parts are distinctly visible.

Using Blackwell's data [9], the contrast threshold, using 50% probability of detection, is approximately 0.01 for a mark of 30 minutes diameter and 0.02 for a mark of 10 minutes diameter. If a correction factor of 2 is used to obtain thresholds more nearly corresponding to the usual criteria of detection, threshold values of 0.02 and 0.04 are obtained for marks 30 and 10 minutes in diameter.

Contrast threshold values obtained during the period of the transmissometer calibration varied but are all greater than 0.02. A computation of ε based on Hulburt's data [50], in which the visual range was described as the distance at which an object could *just not be* seen, yields a value of 0.027. Houghton [48] reported a yield of 0.065 for clouds and about half that for fog. Duntley [31] reported that a comparison of "visibility", as determined by the staff meteorologist at the Tiffany Foundation, and measurements of beam transmittance was in agreement with what is now the transmissometer calibration. Muench, et al [100], in their calibration of a forward scatter visibility meter, report a correlation between routine weather observations and the extinction coefficient which are in agreement with the transmissometer calibration.

From the foregoing, it appears that the use of a recognition contrast threshold value of about 0.05 when measurements of transmittance are used for determining the visual range equivalent of that reported by meteorologists and vice-versa and the use of a value of ε in the region 0.035 to 0.04 for a detection contrast threshold under field conditions will give reliable results.

Recognition contrast threshold values, such as those used in the transmissometer calibration are applicable to situations in which the observer is deliberately searching for a particular mark of known approximate location with adequate search time. When the attention of the observer must be attracted, when the approximate location of the mark is not known, or when the search time is limited, the values of contrast threshold are higher. When the location of the object is known precisely and recognition is not a criterion, the values of contrast threshold are lower.

4.3 VISUAL RANGE OF LIGHTS

4.3.1 Historical

Work of Bouguer and Allard. The following equation, which gives the illumination from a point source of light at any distance in a partly transparent medium, is known as Allard's Law:

$$E = I\, e^{-\sigma x}/x^2 \,, \qquad (4.21)$$

where E is the illumination at distance x from a source of luminous intensity I in a medium of extinction coefficient σ.

If the illuminance threshold E_t is substituted for E in equation 4.21, the corresponding value of x will be the visual range V, as follows:

$$E_t = I\, e^{-\sigma V}/V^2 \qquad (4.22)$$

which can then be solved for V, yielding

$$V = [\ln(I/E_t) - 2 \ln V]/\sigma \ . \tag{4.23}$$

Although the foregoing law was indeed published by Allard in 1876 [3], Middleton [93], in his role as a historian of science, has found that Bouguer had stated this law much earlier, in 1729.

Work of French Lighthouse Service. The French Lighthouse Service developed an early interest in the visual range of lights--an interest which began in the mid-seventeenth century. An 1864 work by Reynaud [111] documents this work*, much of it under the leadership of Allard and Fresnel. The French conducted experiments in the mid 1800's to determine appropriate values of the transmissivity, T, under a number of different atmospheric conditions. Reynaud's remarks indicate that the work of Bouguer provided the basis for the French Lighthouse Service experiments. Bouguer had assigned to T a value of 0.973/kilometer for a "clear calm atmosphere".

In 1876, Allard published his famous Memoire reviewing his work on the visual range of lights. Reynaud's manual does not specifically credit Allard with the law. The French Lighthouse Service, when questioned as to the originator of the law, responded with a photocopy of an unsigned memorandum which could be attributed "only to Allard". See Appendix B.

Allard expressed equation (4.22) in terms of transmissivity, thus

$$E_t = I \ T^V/V^2 \ . \tag{4.24}$$

This is the most common expression of Allard's law.

4.3.2 Analysis of Allard's Law:-

Using this terminology (4.23) may be written as

$$V = [\ln(I/E_t) - 2 \ln V]/\ln T \ . \tag{4.25}$$

Equations (4.23) and (4.25) can not be solved directly for the visual range V. Graphical and iterative approximations must be used. See Section 4.4.6.

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*This work was of sufficient importance that it was translated into English, in 1876, by Peter C. Haines.

The equations given above are strictly applicable only when the luminance of the background is small compared to the average luminance of the light. Otherwise Equation (4.22) becomes:

$$E_t = [I - (L - L')\,A]\ e^{-\sigma V}/V^2 \qquad (4.26)$$

where L is the luminance of the background of the light, L' is the average luminance of the unlighted projector, both in candelas per unit area, and A is the area of the entire projector projected on a plane normal to the line of sight.

Both L and L' are measured in the direction of the line of sight from a position near the light.

Since the intensity of a light source is the product of its area and its average luminance, equation (4.26) may be written

$$E_t = [L_e - (L - L')]\ A\ e^{-\sigma V}/V^2 \qquad (4.27)$$

where L_e is the average luminance of the light source.

The quantity (L - L')A is the intensity required of the light to make its average luminance equal to that of the background. The visual range of the light is determined by the net intensity, that is, the difference between the measured intensity of the light and this intensity. Typically the term (L - L')A has a significant effect on the visual range of a signal light only under daylight conditions when the light is dimmed or when the light has a low average luminance in the direction of view. For example, an approach light has a luminance, L_e, in excess of 100,000 candelas per square foot when operated at full intensity without filters. The inherent luminance of the background, L, will exceed 1000 candelas per square foot only on very rare occasions. Hence, L is less than 1% of L_e. On the other hand, when these lights are dimmed to Step 1, 0.2% of full intensity, the luminance of the light is reduced to 200 candelas per square foot, and the effect of background luminance in (4.27) may be very significant. Filters will reduce the luminance of the light to about 15% of the unfiltered intensity for red and green, and to about 2% for blue. Omnidirectional lights, such as taxiway lights and obstruction lights have a luminance, when lighted, of less than 500 candelas per square foot and the effect of background luminance in

(4.27) is highly significant.

4.4 ILLUMINANCE THRESHOLD

The value of illuminance threshold, E_t, to be applied in Allard's law, (4.22 and 4.24) in transmissivity-visual range computations has been of concern since the days of Allard and, in the early days of night flying, Langmuir and Westendorp made a comprehensive study of illuminance thresholds applicable to aviation [87].

The illuminance threshold is not a constant. It is a function of the luminance of the background of the light, the position of the light in the field of view, the angular size and shape of the light, its color and, if not steady burning, its flash characteristics. In addition, the observer's knowledge of the position of the light and his time for search have a significant influence on the threshold.

4.4.1 Illuminance Threshold for "White" Point Sources

Figure 4.4 shows the relation between illuminance threshold and background luminance for steady burning, white, point sources for about 98 per cent probability of detection. The illuminance threshold values shown are applicable only when the observer knows precisely where to look for the light. Even if the illuminance is twice the values shown the light will be hard to find. The illuminance values must be increased by a factor of 5 to 10 if the light is to be easy to find [118].

These increases in threshold illuminance are applicable only when the observer is looking for the light signal. Much greater increases are needed if the light signal is to attract the attention of an observer who is not searching for it. Factors of 100 and 1000 are not excessive [51].

The break in the curve (the knee of the curve) in figure 4.4 represents the change from cone to rod vision. At low background luminances, the illuminance threshold for cone vision remains essentially unchanged as indicated by the dashed line. The dashed horizontal portion of the curve represents most night seeing conditions since a light used as a signal is usually observed by looking directly at it; hence cone, not rod vision, is used. Moreover, it is doubtful whether those engaged in transport, even lookouts on ships, even reach the state of dark adaptation

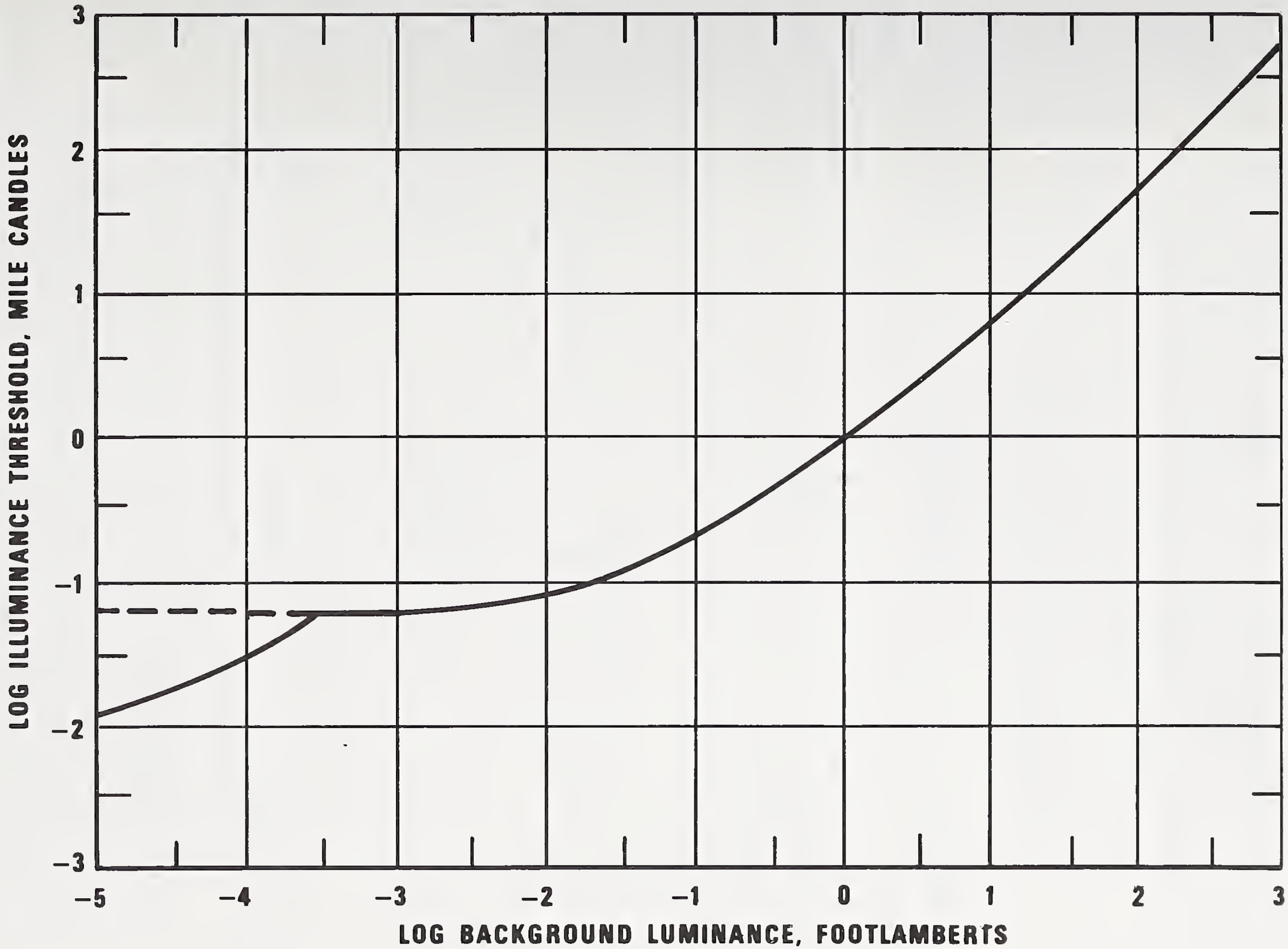


Figure 4.4 Minimum illuminance at the eye from an achromatic (white) point source for about 98 per cent probability of detection as a function of the background.

required for rod vision [11].

Representative background luminances are given in table 4.1. It should be noted that the luminance of the night sky in the vicinity of cities and airports seldom falls below 0.001 footlambert because of the effects of man-made sources [114]. Note also that, unless there are glare sources in the field of view, it is probably necessary to consider only the background in the immediate vicinity of the light [77].

TABLE 4.1

Luminances of Backgrounds Against Which Light Signals are Viewed

Background	Background Luminance (footlamberts)	Candelas per square meter
Horizon sky		
Overcast, no moon	0.00001	0.000034
Clear, no moon	.0001	.00034
Overcast, moon	.001	.0034
Clear, moonlight	.01	.034
Deep twilight	.1	.34
Twilight	1	3.4
Very dark day	10	34
Overcast day	100	340
Clear day	1000	3400
Clouds, sun-lighted	10000	34000
Daylight fog		
Dull	100-300	300-1000
Typical	300-1000	1000-3000
Bright	1000-5000	3000-16000
Ground		
On sunny day	100	300
On overcast day	10-30	30-100
Snow, full sunlight	5000	17,000

4.4.2 Effects of Source Size

As stated earlier, the values of illuminance threshold shown in figure 4.4 are applicable only to lights which are, in effect, point sources. A light source behaves as a point source if the angle it subtends at the eye is below a certain size called the critical angle. For sources subtending angles below the critical angle, the eye responds to the intensity of the source, that is to the product of the luminance of the source and the solid angle subtended by the source. This relation was reported by Ricco in 1877 and is sometimes called Ricco's Law. Critical visual angle is plotted as a function of background luminance in figure 4.5 and shows the critical angle below which Ricco's Law is valid. This critical angle increases as background luminance decreases.

When the critical visual angle is plotted as a function of background luminance, as in figure 4.5, it provides a practical definition of a point source--a stimulus which affects the eye only in proportion to its intensity.

Most aviation signal lights behave as point sources at distances near the visual range of the lights, as is evident from the following example. From figure 4.5 it is seen that at a typical nighttime background luminance of 0.01 footlambert, the critical angle is of the order of 2.5 minutes. The diameter of U.S. approach lights is 7 inches. A source of this diameter subtends an angle of 2.5 minutes or less for all distances greater than 700 ft.

When a light source subtends an angle larger than about 1° its visibility is determined not by its intensity, but its luminance (intensity per unit area). Thus, increasing the size of a large source at threshold visibility, without increasing the luminance, increases the intensity, and the corresponding illuminance at the observer's eye, but does not increase the visual range. However, if the size of a point source at threshold is increased, maintaining the luminance constant, and if, after the increase in size, it is still a point source, the visual range is increased.

There is a transitional range of angular sizes in which the light can be considered neither as a point source or as a large source. This region has been studied by deBoer [25]. Correction factors called "size factors" have been computed from his study. Approximate thresholds for sources which are too large to be considered point sources may be obtained by multiplying the thresholds obtained from figure 4.4 by these size factors which are given in table 4.2.

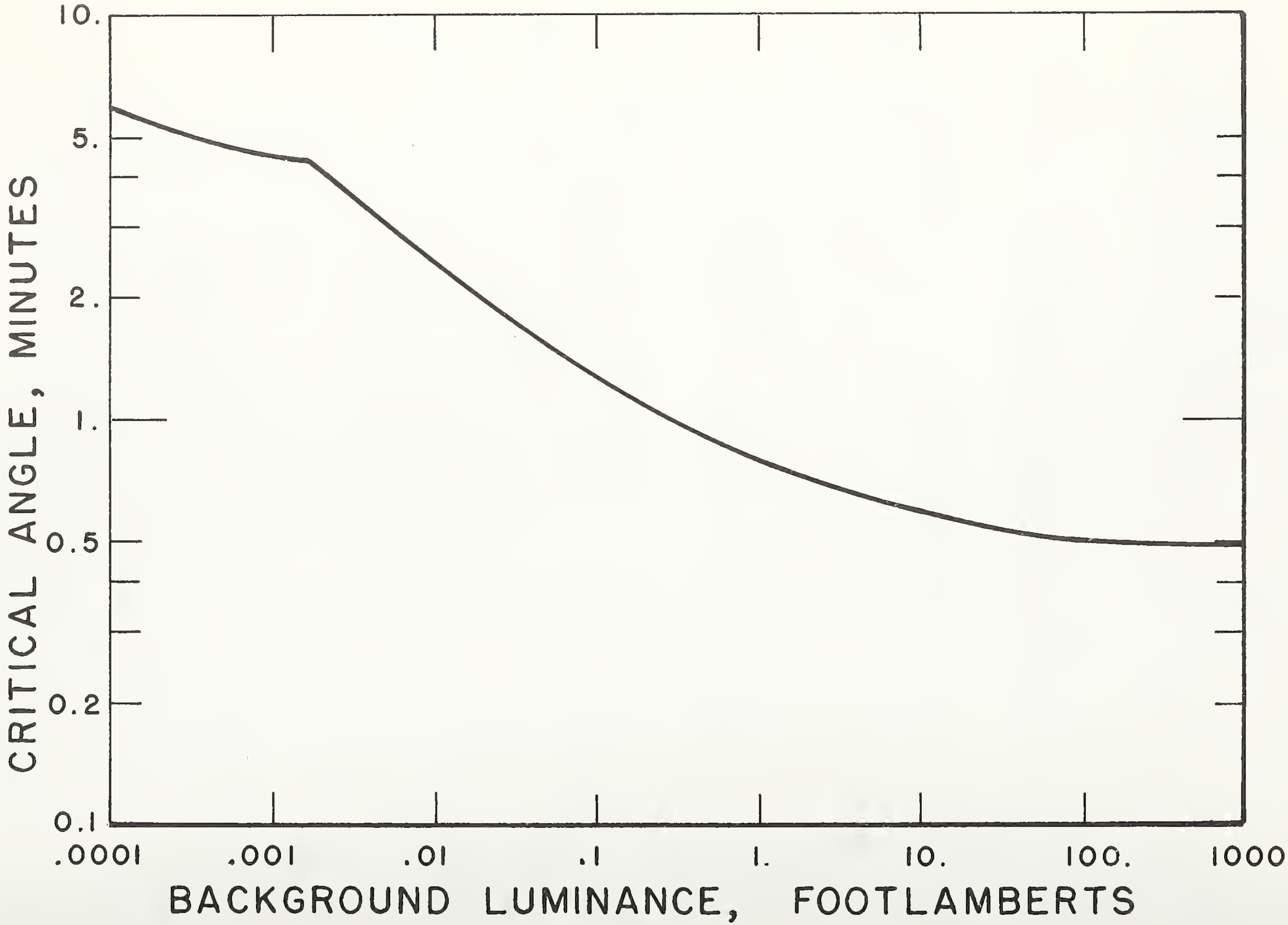


Figure 4.5 Maximum angular diameter of a circular source which can be considered strictly as a point source (after Blackwell [9]).

TABLE 4.2

Size Factors for Obtaining Thresholds for Sources Other Than Point Sources

Ratio of Source Diameter to Viewing Distance	SIZE FACTOR Night	SIZE FACTOR Day
0.0005	1.0	1.0
0.001	1.0	1.2
0.003	1.1	2.5
0.005	1.4	4.9
0.01	2.5	20.0

Figure 4.4 and table 4.2 apply only to threshold and near threshold viewing. with the observer looking directly at the light. In an investigation of optimum intensity of road traffic signal light intensity, Cole and Brown [21] found that the intensity of a red traffic signal light required to produce optimum recognition under bright daylight conditions and peripheral viewing is independent of source size for sources subtending up to 16.5 minutes of arc. These findings extend the effects of Ricco's Law over a much greater field of view.

4.4.3. Illuminance Threshold for 'Composite' Light Sources

In aviation lighting the approach light units are barettes of several sealed-reflector lights spaced a few feet apart. Likewise the VASI light box is comprised of 3 separate but closely spaced lights.

It is well known that, when observed at sufficiently great distances, a light unit of this type may be considered as a point source with the intensity being the sum of the intensities in the direction of view or all of the lamps of the light. When a light of this type is observed at sufficiently short distances, the effective intensity of the unit will be approximately that of a single lamp of the unit. Either of these extreme distances may be outside the range for which the approach-light system is most useful.

The importance of considering this factor has been studied in the laboratory for deBoer [25] and observed experimentally at Arcata [101].

DeBoer developed a "row" factor, which is a measure of the "mutual assistance" of the lights in the row, to apply to composite sources in which the distance between lamps is so great that the light cannot be considered as a simple rectangular unit of uniform brightness. If the composite unit is considered as a group of individual sources, each assisted by the adjacent lamps, the intensity of a single lamp plus the "assistance" of the adjacent lamp may be computed by means of deBoer's "row" factor.

The Arcata tests verified the general principles of deBoer's "row" factor. However, no application has been made of this concept and visual range computations are usually based upon the intensity of a single lamp. Further study is needed.

4.4.4. Illuminance Thresholds for Flashing Lights

Blondel and Rey [12] found that the illuminance threshold for a square-wave flash (a flash producing a relatively constant illuminance throughout its duration) is given by

$$E = E_t(a + t)/t ,$$

where E_t is the illuminance threshold for a steady light, t is the flash duration and 'a' is a constant. The value used for 'a' is usually 0.2 for lights viewed at threshold at night.

However, in the computation of the visual range of flashing lights, it is more convenient to use the illuminance threshold for a steady-burning light and to apply the concept of effective intensity in determining the intensity to be used in Allard's law (4.22) and (4.24).

The effective intensity, I_e, is defined as

$$I_e = I\ E_t/E ,$$

or

$$I_e = I\ t/(a + t) , \qquad (4.28a)$$

where I_e is the effective intensity, and I is the instantaneous intensity producing the illuminance E.

The flash from most lights used in aviation service, such as airway beacons and anti-collision lights, is not abrupt. The instantaneous intensity often rises and falls gradually and may vary appreciably during the flash.

In a subsequent paper, Blondel and Rey [13] proposed the following modification of equation (4.28a).

$$I_e = \int_{t_1}^{t_2} I \, dt/(a + t_2 - t_1) , \qquad (4.28b)$$

for flashes which were not abrupt. The limits t_1 and t_2 are the times at the beginning and end of flash respectively. This proposal was based on intuitive grounds.

There has been little experimental verification of equation (4.28b) However, in a field test conducted in fog at Arcata by the Visual Landing Aids Laboratory of the National Bureau of Standards [102], the following values of 'a' were obtained:

TABLE 4.3

Values of the "Blondel-Rey Constant" Obtained at Arcata

	DAY		NIGHT	
Flash Duration	'a'	# of Observations	'a'	# of Observations
20 microsecond	0.24	(317)	0.44	(258)
200 microsecond	0.13	(407)	0.33	(253)
0.3 second	0.23	(175)	0.40	(152)
0.5 second	0.18	(50)	0.39	(92)
Weighted Average*	0.19	(949)	0.39	(755)

*Weighted in accordance with the number of effective intensity observations used in the determination of the value of 'a'.

The general agreement of the values of 'a' obtained for different flash lengths indicates the usefulness of equation (4.28b).

The effective intensity of most flashing lights is now in terms of equation (4.28b) using 0.2 as the value of 'a'.

For a more extended discussion of effective intensity see Douglas [27] and Projector [109].

4.4.5 Illuminance Thresholds for Colored Light Sources

Illuminance thresholds for colored lights fall into two categories: a) the achromatic illuminance threshold which is based upon the criterion that the light is visible but that the color need not be recognized and b) the chromatic illuminance threshold which is based upon the criterion that the color must be recognized, resulting in somewhat higher illuminance thresholds. As visual range in practice is based upon achromatic thresholds, only they will be discussed here.

There are many laboratory studies of color recognition but only a few use sources of an angular size sufficiently small to simulate signal lights. Among these are those of Hill [43], Middleton and Gottfried [97], Middleton and Wyszecki [96], and Jainski and Schmidt-Clausen [74]. The results of these studies are in reasonably good agreement. For sources which may be considered as point (or near-point) sources, the order of increasing illuminance threshold is red, yellow, white, green, and blue.

Typically, the illuminance threshold for red is about half of that of white, and the illuminance threshold for blue is about twice that of white. The differences between yellow, green, and white thresholds are small.

The fact that a red light is more visible than its "photometric" intensity indicates it would be, has been independently discovered many times; for example, by the French Lighthouse Service in 1864 [111], deBoer [25], Middleton and Gottfried [97], and Projector [110].

4.4.6 Curves Relating Atmospheric Transmissivity, Intensity, and Illuminance Threshold

As stated earlier, Allard's Law, (4.22) and (4.24), can not be solved directly for the visual range, V. Hence, it is not possible to compute simple equations giving visibility factors showing the effects of intensity, illuminance threshold, or transmissivity upon visual range. In this section, several graphs are presented illustrating the effects of these parameters and making possible graphical solutions of Allard's Law for V.

It will be apparent from these curves that in fog the law of diminishing returns takes effect at relatively short distances. For example, if the transmissivity is 0.01 per mile (light fog), a light with an intensity of 100 candelas will produce an illuminance of one mile candle at a distance of one mile; an intensity of 40,000 candelas is required to produce that illumination at 2 miles; and 9,000,000 candelas is required at 3 miles.

In figure 4.6 the intensity required to produce an illuminance of one lumen per unit area has been plotted as a function of distance for several values of atmospheric transmissivity. The curves of this figure demonstrate the importance of the fact that the intensity is attenuated exponentially with distance and can be used to graphically solve the various forms of Allard's law. The curves can be used with any consistent set of units; for instance, I in candelas, D in miles, E in mile candles (lumens per square mile), and T per mile.

The figure can be used for thresholds other than one lumen per unit area by simply dividing the ordinate scale by the illuminance threshold. For example, if a daytime threshold of 1000 mile candles is assumed, D would be stated in miles and each intensity shown on the ordinate scale would be divided by 1000. Thus 10^6 candelas would become 10^3 candelas.

The curve T = 0.70 (per mile) is representative of average visibility conditions, while that for T = 0.90 (per mile) represents an unusually clear condition. Note that at a distance of 10 miles, the intensity required to produce unit illumination for average conditions (T = 0.70), is approximately 12 times that required for conditions when T = 0.90, assuming an illuminance threshold on the order of one mile candle. At a distance of 20 miles, it is approximately 150 times greater. It is also evident from a comparison of the curves T = 0.90 and T = 1.00 that even for a very clear atmosphere the transmissivity cannot be disregarded when the distance to the source is large.

A series of nomographs which permit a precise solution of Allard's Law for V, or any of the other parameters, and instructions for their use is given in Appendix C.

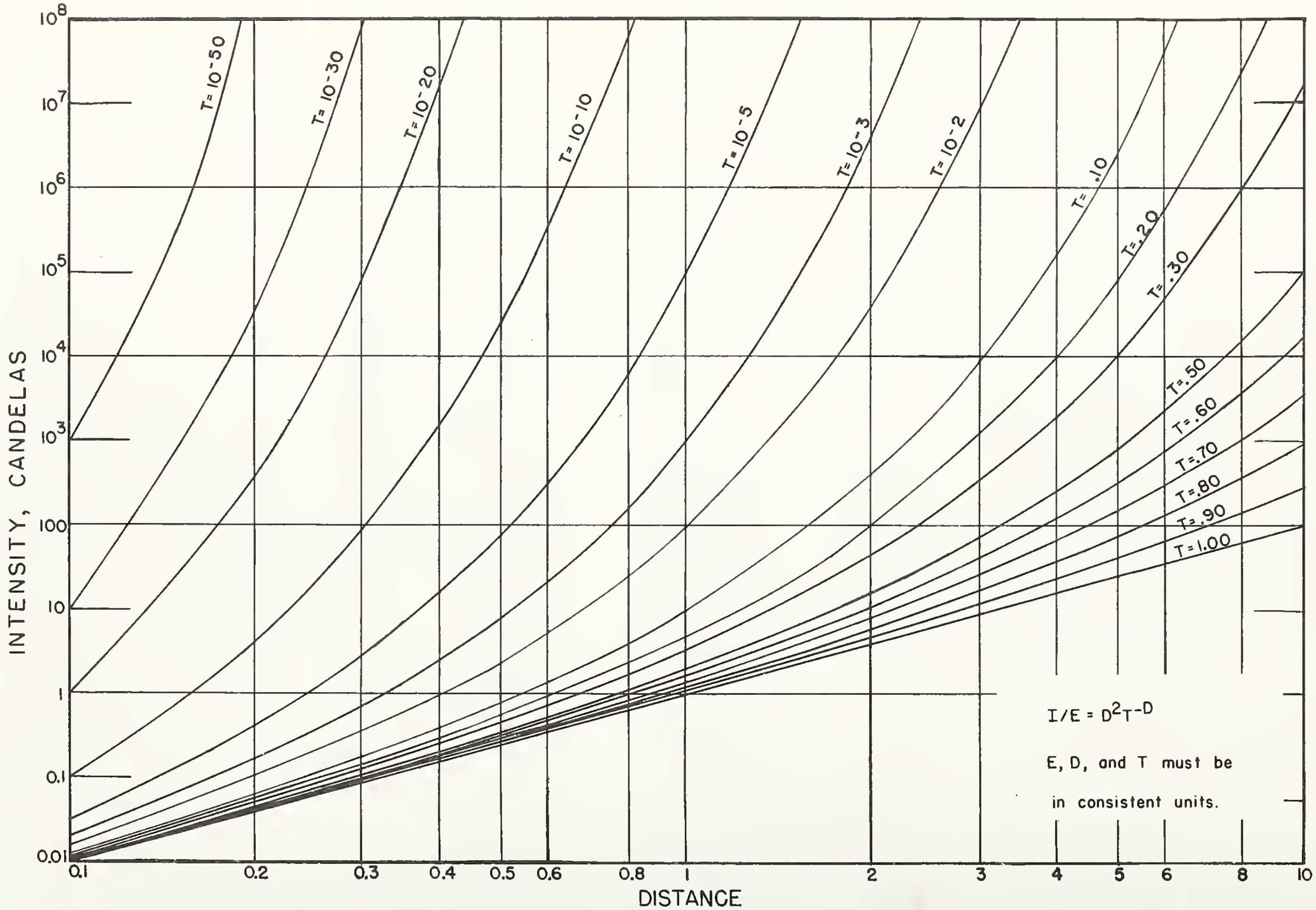


Figure 4.6 The intensity required to produce unit illuminance as a function of distance for several atmospheric transmissivities. Any consistent set of units may be used.

4.4.7 Illuminance Threshold Criteria

The illuminance threshold is a function of both background luminance (see Section 4.4.1) and the type of vision used by the observer. In the Nantucket observations, foveal vision was used to determine whether the light was seen steadily or not, although parafoveal vision may have been used to locate the light. Background luminance was usually on the order of 10^{-3} to 10^{-2} footlambert. In this region, there is little change in foveal sensitivity with the background luminance. These conditions are believed typical of those for most meteorological observations. The combined effect of lights from surrounding areas and from an airport itself make background luminances of less than 10^{-3} footlambert unlikely.

The effects of observers' criteria (i.e., recognition versus detection) upon the determination of contrast threshold (objects by day) were discussed in Section 4.2.2. There are similar effects, according to observers' criteria, when determining the illuminance threshold (lights by night).

The effect of differences in threshold criteria was investigated using the same method as for objects by day. The ratio of the distance at which an observer, knowing the approximate location of the light, can just detect it to the maximum distance at which an observer can see the light steadily was found to be 1.06 for visual ranges in the region of 1000 feet. The spread of the values obtained for this ratio was small, indicating again that the principal cause of the spread of the points of the measurements is the "sampling error", resulting from the measurement of a different path in the atmosphere than that through which the lights were viewed.

If E_1 is the recognition threshold when a light at distance D can be seen steadily and E_2 is the detection threshold at distance $(1 + k)D$,

then

$$\ln(E_2/E_1) = k\ D \ln T - 2 \ln (1 + k)$$

or, since k is small,

$$\ln (E_2/E_1) = k D \ln T - 2k$$

Using this equation, the detection threshold was found to be 0.6 times the recognition threshold. The recognition threshold for night observation at Nantucket was found to be 0.052 kilometer candle when the light was at a distance of 1 kilometer. The corresponding detection threshold is 0.031 candle. The values of both these thresholds are in good agreement with the small amount of data obtained in clear weather at Arcata.

A very few data were taken at Arcata to obtain the 50% detection threshold. A value of 0.02 km candle was obtained with a background luminance of approximately 0.005 footlambert.

A recognition threshold of about 150 km candles was obtained at Arcata in daylight with background luminances from 500 to 700 footlamberts. The corresponding detection threshold is 100 km candles. Again the data are few.

Kevern's report [76] can be used in comparing laboratory values with the field values discussed thus far. Kevern computed from Blackwell's [9] data the illuminance threshold in mile candles for an effective point source, for a variety of background luminances, using a threshold criteria of 50% detection. The illuminance threshold obtained for a background luminance of 10^{-3} to 10^{-2} footlambert is 0.032 mile candle (0.012 km candle). For daylight conditions, with a background of 700 lamberts, the detection threshold computed from Kevern gives a value of 64 mile candles (25 km candles). If these values are increased by a factor of 2, to obtain values more nearly corresponding to the usual criteria of detection thresholds, then values of 0.025 and 50 km candles are obtained for background luminances of 0.005 and 700 footlamberts. Detection thresholds of 0.034 and 24 km candles were obtained from data reported by Knoll, Tousey and Hulburt [77] for background luminances of 10^{-2} and 700 footlamberts.

The results of these determinations are summarized in table 4.4.

Table 4.4

Illuminance thresholds (km candles)

	Night		Day	
	Detection	Recognition	Detection	Recognition
Nantucket	0.031*	0.052*	-	-
Arcata	0.02	-	100	150
Kevern	0.025	-	50	-
NRL	0.034	-	24	-

*At a distance of one kilometer.

Thus the values for illuminance threshold obtained in field experiments during periods of fog do not differ greatly from those obtained in the laboratory when the same criteria of threshold are applied.

4.4.8 Thresholds Applicable to the Aircraft Pilot

NOTE: In analyzing flight test data and in computing visual range from aircraft, it is convenient and conventional to consider the illuminance incident on the windscreen, not on the pilot's eye as the illuminance used in Allard's law. Thus a correction must be applied to laboratory threshold data and to field threshold data obtained from outside the cockpit when applying it to aircraft situations. The correction factor for a modern air carrier aircraft is estimated to be 2. This factor has been often ignored in applying laboratory data to flight situations.

4.4.8.1 Nighttime Thresholds for Pilots

It should be apparent that the illuminance thresholds given in figure 4.4 are not directly applicable to the pilot.

An illuminance threshold of 0.5 mile candle (0.2 microlux) was chosen as the illuminance threshold applicable to pilots in the 1930's [117]. This value was also accepted as applicable to shipboard lookouts at the International Technical Conference on Lighthouse

Authorities, Paris, 1933. Because of the increase in the complexity of the flying task, the great increase in the number of lighted instruments, and the increased losses in aircraft windscreens, a number of workers in the field of aviation lighting used an increased threshold illuminance of 1 mile candle (0.4 microlux) in the 1940's. Later this value was increased to 2 mile candles (0.8 microlux) in the U.S. at the start of the runway visual range program. At the same time, but independently, a value of 1 microlux (2.5 mile candles) was recommended by the International Commission on Illumination. [72]. A value of of 0.87 microlux (2 mile candles) has been recommended to the International Civil Aviation Organization by the All Weather Operations Panel [58].

The choices of illuminance threshold were based primarily upon engineering judgment with little, or no, hard evidence. Note that a threshold of 2 mile candles ia about 40 times the illuminance threshold shown for a background luminance of 10^{-3} footlambert in figure 4.4. An illuminance of 2 mile candles is about the value of the minimum useful signal found by Breckenridge and Douglas [16]. In 1966, Lefkowitz and Schlatter [90] analyzed the flight test data of the Landing Aids Experiment Station and of the MacArthur Field tests and obtained values for illuminance threshold, based upon a 50% probability of sighting, of 1.6 and 5 mile candles respectively for the pilot's sighting of runway edge lights. The flight test data obtained at Newark, based upon the pilot's sighting of the green threshold lights, was also analyzed. These data showed illuminance thresholds of 0.9, 2.5, and 30 mile candles for runway light settings of 4, 20, and 100% respectively. Although no statement of the approach light intensity is made, these lights were presumably operated at the same intensities as the runway lights. These Newark data were the first flight test data obtained with a high intensity Configuration A approach light system. They provide a clear indication of the effects of light intensity setting on the pilots nighttime illuminance threshold. The data are in general agreement with the analysis made by Simeroth [114] of the self-defeating effects of increasing approach and runway light intensity on the pilot's illuminance threshold.

The nighttime data taken at Atlantic City in 1959 and 1960 [90] appear to be strongly influenced by the effects of a dense cloud cover overlying the fog. A nighttime threshold of 1000 mile candles was obtained. The spread of the data was very large. Whereas in the laboratory the ratio of the illuminance threshold for 95% probability of seeing to the threshold for 5% probability of seeing is about four, in the flight test data analyzed the ratio was in the range 1000 to 10,000. Hence the uncertainty in thresholds obtained from data of this type is very large.

It should be noted that when the decision was made (see Section 3.9.1) to use a fixed nighttime illuminance threshold of 2 mile candles, the nighttime luminances of fogs, as seen from the glide path or runway centerline, were about one tenth the luminance of fogs of the same density today. The increase in luminance results from the addition of high intensity, wide beam centerline and touchdown zone lights and the use of Configuration A approach light systems with wide beam lights. Not only have the number of lights and the lumen output per light both increased, but in addition, these lights are located closer to the center of the visual field. Thus, the effects on the illuminance threshold of the changes in fog luminance with the intensity setting of the lights are greater today than they were at the time the system was designed. Theoretical analyses [107, 114], ground observations [90], and flight tests [34, 90] confirm the need for a consideration of these effects in assessing RVR. See also Section 3.9.2.

A complete analysis of the many parameters which influence the RVR nighttime illuminance threshold is beyond the scope of this document. There is, however, one misconception which should be noted here. In the considerations of the All Weather Operations Panel, an illuminance threshold of 2 mile candles has been justified for background luminances typical of fog luminances with present lighting systems (1 to 15 footlamberts, 4 to 50 candelas/meter^2) because this choice is in agreement with Blackwell's data [9] and other threshold data. However, in reaching this conclusion, no consideration was given to the conditions under which Blackwell's data are applicable, namely a 50% detection probability by an observer whose sole task is to look for a light of known location and occurrence. For a 98% detection probability, the illuminance threshold must be doubled.

(See figure 4.4). Additional increases of from two to ten are required if the pilot does not know exactly where to look [51]. A further increase of as much as two is required to compensate for losses in the aircraft windscreen. Thus, an increase on the order of ten to twenty in the nighttime RVR illuminance threshold is appropriate for conditions in which the fog luminance is on the order of 1 to 15 footlamberts.

4.4.8.2 Daytime Thresholds for Pilots

Lefkowitz and Schlatter, in their study, computed the daytime illuminance thresholds obtained from flight test data. Daytime illuminance thresholds based upon 50% probability of seeing were as follows:

Landing Aids Experiment Station		1000 mile candles
MacArthur Field		20
Newark		600
Atlantic City	20% intensity	1600
	100% intensity	9000

During daylight the effects of the intensity setting of the lights are expected to have little effect on the illuminance threshold. The ratio of 95% to 5% probability of seeing was about an order of magnitude lower than that found at night, being in the range 100 to 1000.

4.4.8.3 Ground Observations at NAFEC

In the study referred to above, Lefkowitz and Schlatter conducted a field study to determine illuminance thresholds applicable to the assessment of runway visual range. Observations were made from a height of 15 ft above the centerline of a runway equipped with runway edge lights (type L-819) and centerline lights (type L-845, improved). The average intensity (see 2.1.5) of the edge lights was approximately 10,000 candelas; the average intensity of the centerline lights, 4500 candelas. Peak intensities were approximately 25,000 candelas and 7,000 candelas for the edge and centerline lights respectively. Edge lights were spaced at 200 foot intervals; centerline lights at 25 or 50 ft intervals as desired.

The illuminance thresholds for 50% probability of seeing were as follows:

N I G H T	100% intensity	2.0 mile candles
	20% intensity	0.8
	4% intensity	0.4
D A Y	100% intensity	110

The night observations show again the effects of the fog luminance produced by the lights themselves on the illuminance threshold.

To be applicable to the pilot, all values listed above should be multiplied by a factor of about 2 to compensate for the light losses in the aircraft windscreen and by an unknown factor to compensate for the forward motion of the aircraft. See Section 4.6.

4.5 RELATION BETWEEN VISUAL RANGE OF OBJECTS AND OF LIGHTS

Since pilots use both natural marks and lights for guidance it is desirable to know the relation between the day and night meteorological visibilities for equal transmissivities. Figure 4.7 shows the relation between the day and night visibilities, V_d and V_n, obtained from the transmissometer calibration curves, figure 3.3. The intensity of lights is taken as 25 candelas. A value of 0.055 is used for contrast threshold. When the atmospheric transmissivity, and consequently the visibility, is very low, a 25-candela light can be seen at night more than three times as far as a large black object would be seen during the day in the same atmosphere. This difference decreases as the visibility improves, becoming two to one when objects can be seen one half mile and equal when the visibility is about 16 miles. When the visibility is greater than 16 miles, objects will be seen further than 25-candela lights.

The relation between the visual range of approach and runway lights and the daytime visibility is important in designing airport runways and approach light systems. If the visual range of lights of practicable intensity is greater than the daytime visibility, the visual range of objects, then lights are of considerable assistance to a pilot.

The intensity required for a light to be seen a distance d by day can be computed from Allard's law, by choosing a value of E suitable for

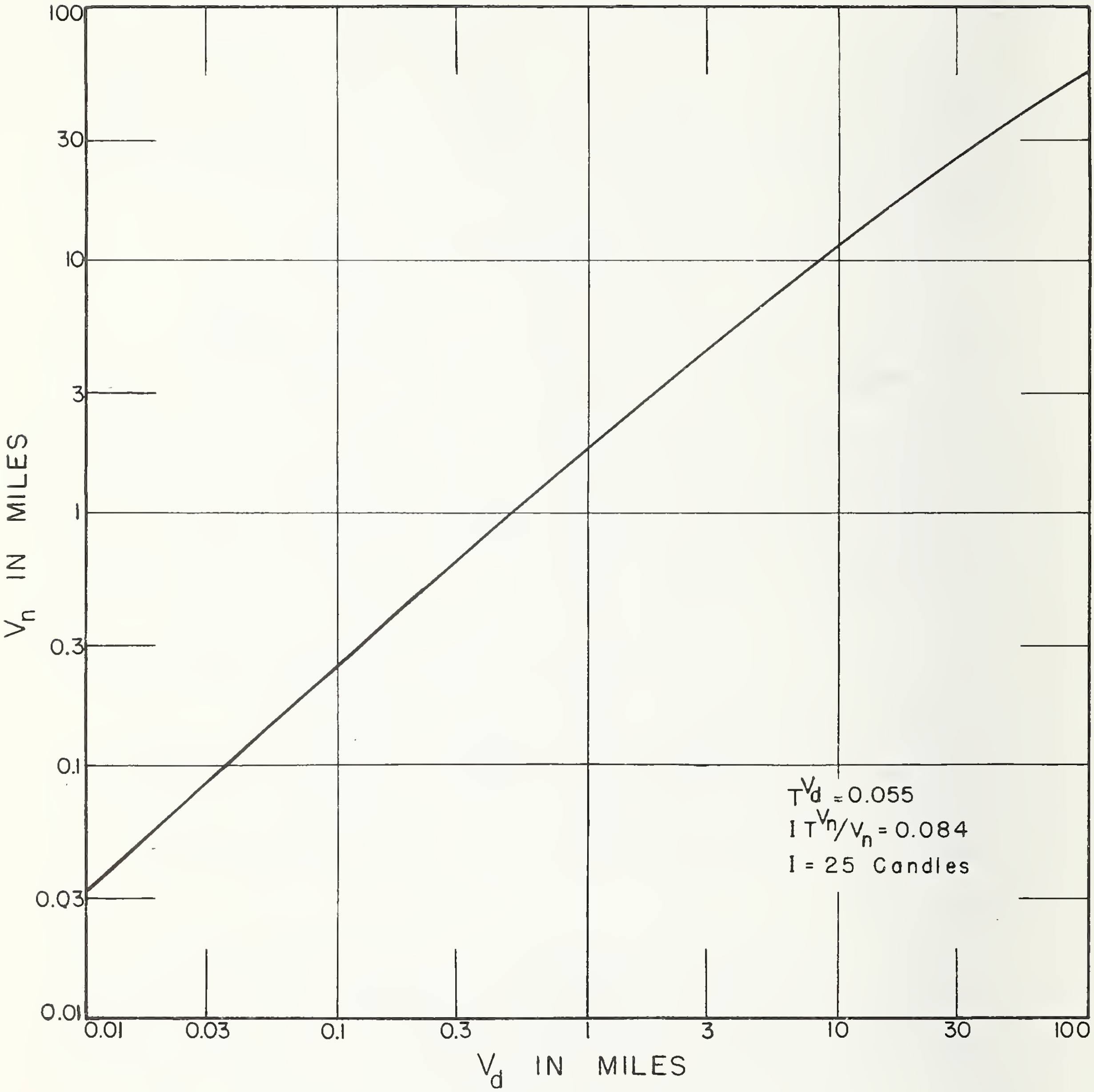


Figure 4.7 The relation between the day and night visibilities indicated by the transmissometer

the prevailing conditions of background luminance. The value of T for the visual range of any given object may be found from Koschmieder's law. The intensities required of lights so that they may be seen at distances proportional to the visual range of black objects can be found on figure 4.8. The value chosen for the background brightness, 1000 footlamberts, is representative of bright daylight fogs. The corresponding value of threshold illumination is 1000 mile candles. This figure shows that in thick fogs lights of even moderate intensity can be seen at distances further than objects.

The use of lights by day is of considerable advantage for the range of visibilities of most concern in the landing of aircraft. A system using approach and runway lights on the order of 25,000 and 10,000 candelas intensity will be seen 1.5 times as far as the object (daylight) visual range during periods of fog.

4.6 EFFECTS OF THE MOVING OBSERVER

The threshold constants applicable to aircraft pilots are considerably higher than those of ground observers because of the longer search times involved. This is due to a number of factors including the pilot's preoccupation with controlling the aircraft, windshield distortion, differences in adaptation, and the absence of cues. It is extremely difficult to find marks or lights which are at or near threshold when their exact position is not known.

An important factor affecting a pilot's search time is the rapid change in transmittance between the pilot and a given mark from the time the pilot is at a point where he would detect it if he were stationary and the time until he actually locates it.

Consider an observer approaching an object at the rate of S feet per second. If C_o is the inherent contrast between the mark and a sky background, C_x the apparent contrast between the mark and its background at a distance x, and C_τ is the apparent contrast after τ seconds, then

$$C_x = C_o T^x,$$

and, where T is the transmissivity (per foot),

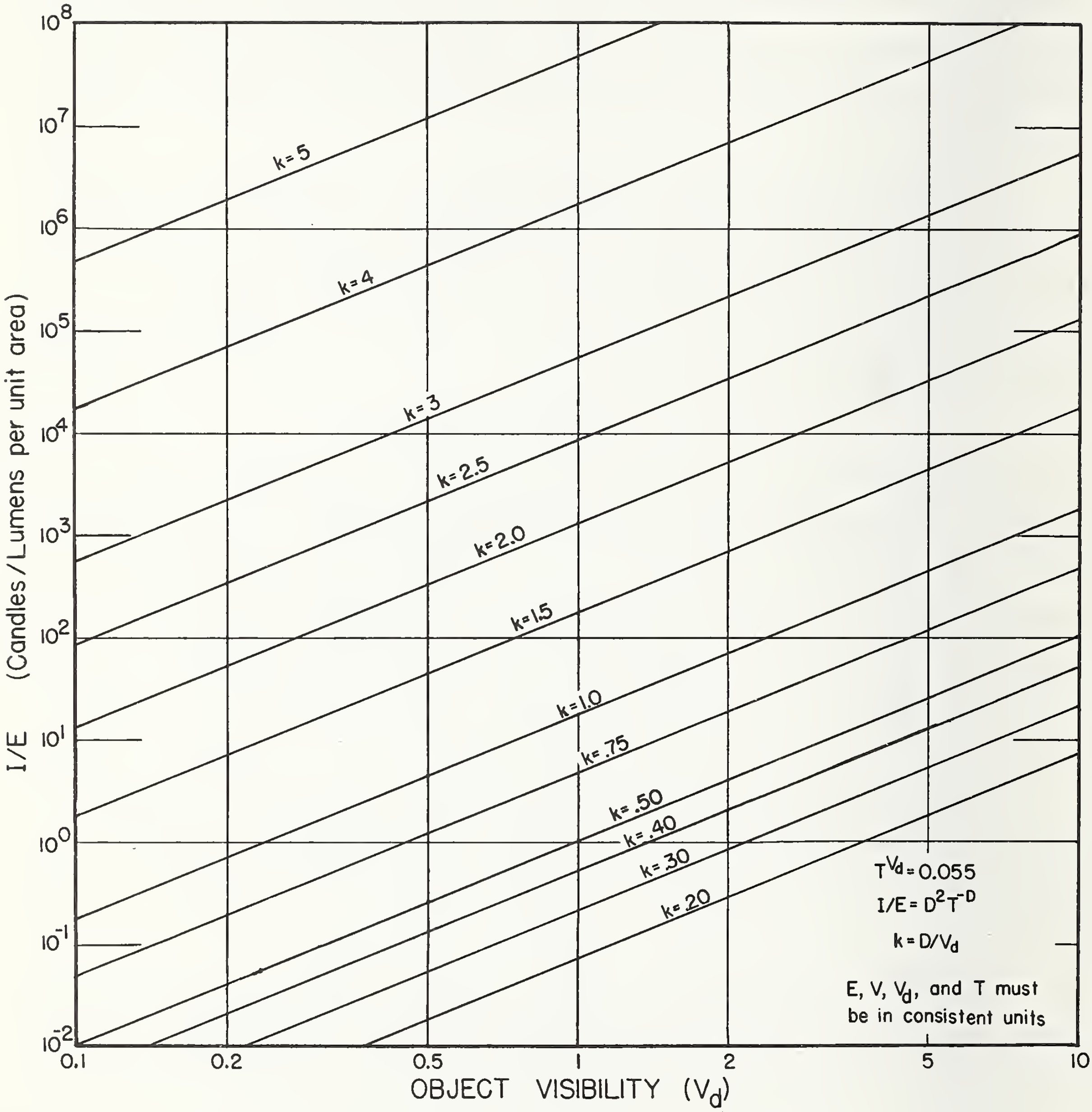


Figure 4.8 Intensity, I, as a function of the threshold illuminance, E, required to produce a visual range K times the daytime visibility V_d.

$$C_\tau = C_o \; T^{x-S\tau}.$$

Thus

$$C_\tau / C_x = T^{-S\tau}. \qquad (4.29)$$

Note that the ratio C_τ/C_x is independent of the distance to the object and is equal to the transmittance of the path traversed during time τ.

Equation (4.29) may also be written as

$$\varepsilon'/\varepsilon = T^{-S\tau} \qquad (4.30)$$

where ε' is the apparent contrast threshold of the moving observer, that is, the contrast threshold which would be obtained if his reported range were used with transmissivity measurements in Koschmieder's law to compute his threshold.

In figure 4.9, the ratio $\varepsilon_\tau/\varepsilon$ has been computed using a value of 200 feet per second for S and a time interval of one second. The figure shows that, even for a search period as short as 1 second, the contrast can increase rapidly when the visual range is low. Thus, by the time a moving pilot has located an object, its contrast, and consequently his apparent threshold, may be much higher than the contrast threshold of a stationary observer.*

Another approach illustrating the effect of the time required to find an object is through the use of the ratio of the apparent visual range to the visual range which would be obtained by a stationary observer. In figure 4.10, this ratio was computed from the relation

$$K = V_p/V_s = (V_s - S\,\tau)/V_s \qquad (4.31)$$

where V_p is the distance at which the pilot will find the object, V_s is the distance at which it could be found if the pilot were stationary, τ is the time in seconds required to find the mark, and S is the speed of the aircraft in feet per second.

*In view of the work of Lamar [81] and others, the assumption of a search time as low as one second may be optimistic.

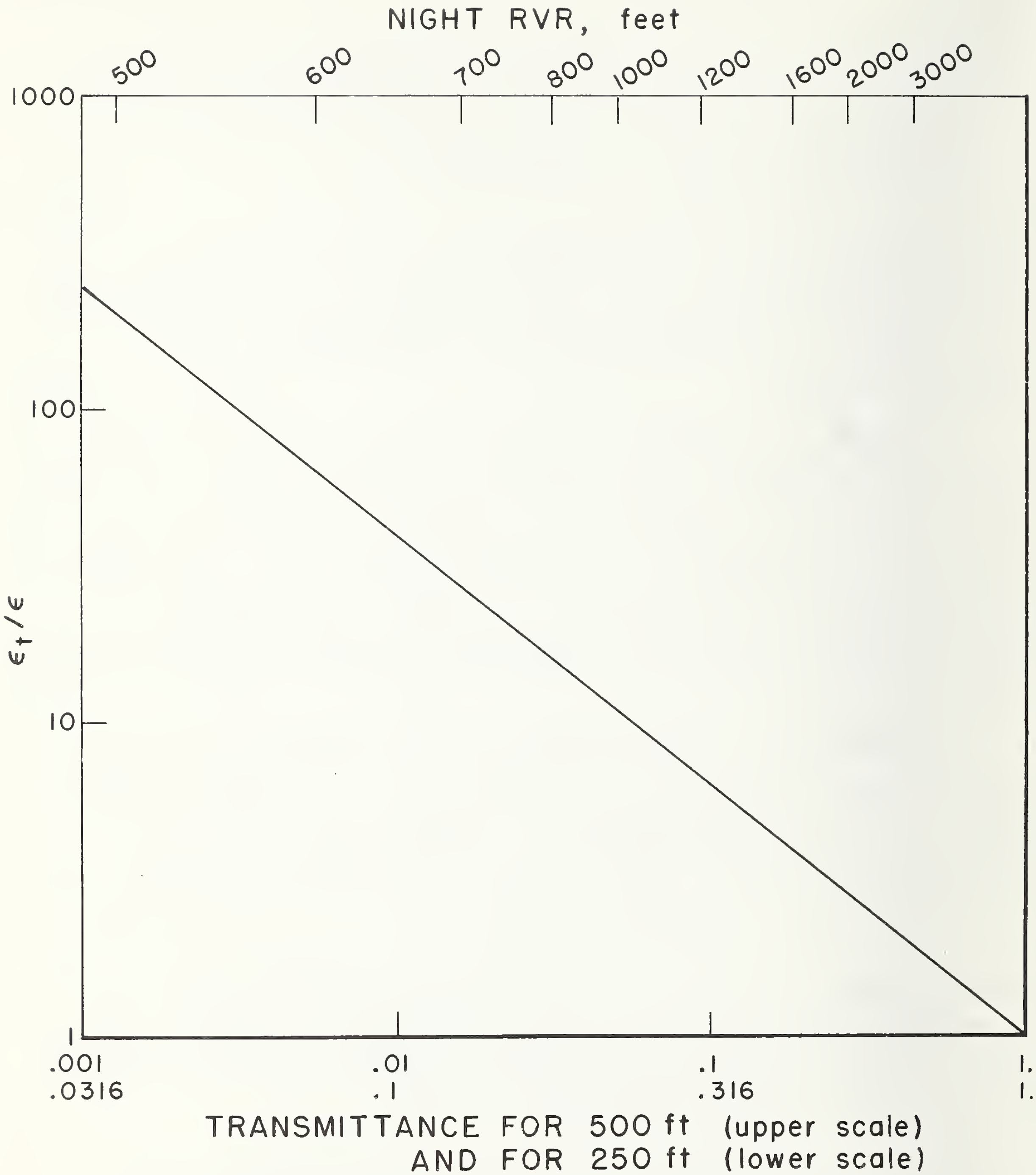


FIGURE 4.9 Effect of speed of moving observer upon his apparent threshold. An aircraft speed of 200 feet per second and a search time of one second have been assumed.

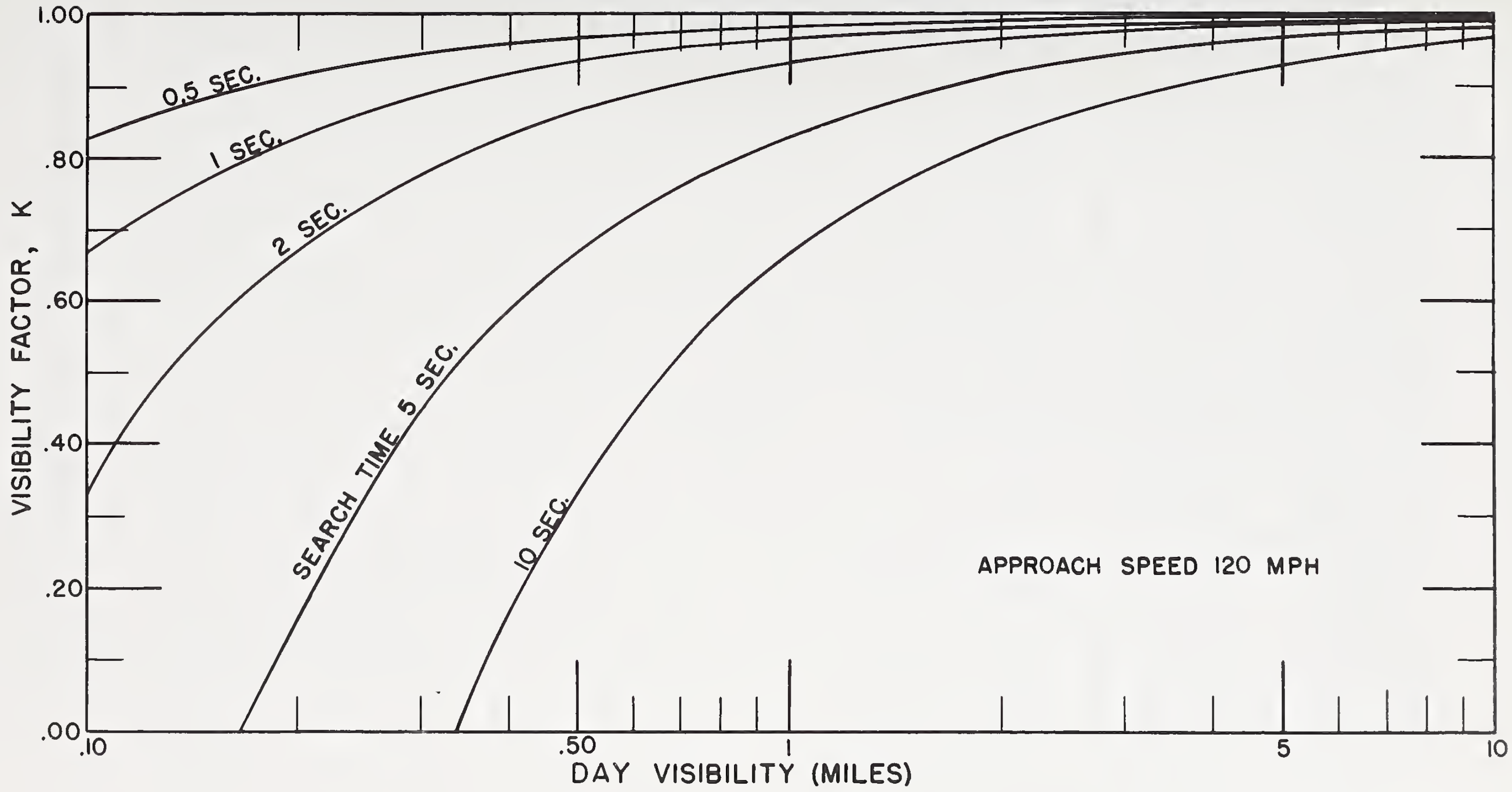


Figure 4.10 Effects of search time on visibility factor

Similarly the change in illuminance from a light can be shown to be

$$E_\tau/E = T^{-S\tau}/(1 - S/x^2) \tag{4.32}$$

where E is the illuminance at a distance and E_τ is the illuminance after τ in seconds. The denomination of (4.32) represents the change in E due to the variation in illuminance with the square of the distance and is always less than 1. Thus the increase in the ratio E_τ/E will be always greater than the increase in the ratio $\varepsilon_\tau/\varepsilon$. Thus figure 4.9 may be considered as representing the lower limit of the ratio E'/E_t where E' is the apparent illuminance threshold of a moving observer and E_t is the illuminance threshold of the stationary observer.

All of the foregoing ratios, and consequently the apparent threshold of a moving observer, are dependent upon both speed and fog density. The apparent spread in the threshold data obtained from flight tests is increased significantly by the effects of search time.

5. MEASUREMENTS OF ATMOSPHERIC ATTENUATION

Note: In this Chapter, primary attention is given to horizontal lines of sight in a uniform atmosphere. Methods of measuring "slant visibility" are beyond the scope of this document.

As shown in Chapter 4, the visual range of objects and lights is directly related to the attenuation of the atmosphere by Koschmieder's and Allard's laws. The transmission of light through the atmosphere is determined by the absorption and scattering which occurs in the light path. Absorption by the fixed gases of the atmosphere is negligible in the visible and near infrared region of the spectrum. Smoke and dust absorb to some extent in the visible region of the spectrum, and, in areas of heavy industrial pollution, the absorption of these particles become significant [122]. Water vapor has absorption bands in the near infrared but absorption in the visible region is not significant. Scattering, therefore, is the principal cause of atmospheric attenuation.

Scattering is a complex function of the ratio of the diameter of the atmospheric particles to the wavelength of light. The air molecules are very small compared to the wavelength of the visible region, and, under these conditions the scattering coefficient varies inversely as the fourth power of the wavelength (Rayleigh scattering). For example, the sky is blue because of the greater scattering of short wavelength (blue) light. The scattering properties of the smaller dust and smoke (Aitken size) particles approach that of Rayleigh scattering. When the diameter of the aerosols is large in comparison to the wavelength of light, the scattering coefficient is essentially independent of wavelength. As the diameter of fog droplets is typically in the range of 2 to 5μ*, and the wavelength limits of the visible

*1μ = 1 micrometer (micron) = 1000 nanometers (nm).

region of the spectrum are about 0.4 and 0.7 μ, the scattering coefficients of fogs and clouds are usually independent of wavelength. Hence the sun usually appears "white" when barely visible through cloud or fog. When the diameter of the aerosols is roughly equal to the wavelength of the light being transmitted, the situation is complex and will not be treated here: For a detailed discussion see Middleton [95], Van de Hulst [120], and Zuev [130].

Many different instruments and methods have been designed to assess the clarity of the atmosphere; each has been chosen to meet the requirements of a particular problem. This report will discuss only those photoelectric instruments which measure the light from a source, transmitted or scattered by the atmosphere. For a discussion of visual instruments and photoelectric instruments which measure the luminance of surfaces at a distance, see Middleton [95], Chapter Nine.

In this report, these instruments discussed will be grouped into two types, as follows:

1. Those which determine the transmittance of a path of known length using a light source and a telephotometer. The transmissivity is then computed from the relationship

$$T = (t_b)^{1/b}, \qquad (2.07)$$

where t_b is the measured transmittance over a path of length b. A block diagram of the NBS transmissometer, a type 1 instrument, is given in figure 3.1. Several types of transmissometers have been described by Oddie [106].

2. Those which measure the flux scattered, from a source, into a receiver by the aerosols present. The output of these instruments is assumed to be proportional to β, the scattering coefficient. However, their output is somewhat dependent upon the size distribution of the aerosols. These instruments can be used to obtain σ, and hence T,

assuming that α, the absorption coefficient, is negligible. This assumption is valid for clean fogs since from (2.10) and (2.13)

$$T = e^{-\sigma} = e^{-(\alpha + \beta)}.$$

Backscatter meters, side-scatter meters, and forward-scatter meters are examples of type 2 instruments which will be covered in this Chapter.

5.1 TRANSMISSOMETERS

5.1.1 Principles of Operation

As previously stated, a transmissometer determines the transmittance of a path of known length using a light source and a telephotometer. The transmissivity is then computed from the relation

$$T = t_b^{1/b}, \qquad (2.07)$$

where t_b is the transmittance over path length b. The transmissivity T is correlated to the visual range of objects using Koschmieder's law,

$$\varepsilon = T^V, \qquad (4.08)$$

where ε is the contrast threshold and V is the visual range. Allard's law,

$$E_t = IT^V/V^2, \qquad (4.24)$$

is used to correlate transmissivity with the visual range of lights at night.

It is essential to note that in both laws distance enters as an exponential. This fact, together with the visual ranges to be determined, governs the choice of distance between the light source and receiver of a transmissometer.

Combining (2.07) and (4.08) yields

$$\varepsilon = t_b^{\,V/b}, \qquad (5.01)$$

which is the basis of the calibration of a transmissometer based on the visual range of black objects.

Similarly, combining (2.07) and (4.24) yields

$$E_t = I t_b^{\,V/b}/V^2, \qquad (5.02)$$

which is the basis of the calibration of a transmissometer based on the visual range of lights.

NOTE: Equations (5.01) and (5.02) strictly apply only to monochromatic light or to an atmosphere which uniformly transmits light of all wavelengths in the wavelength band to which the telephotometer responds or the visible wavelength region, whichever is larger. (See Section 6.4.3.)

Transmissometers may be subdivided according to the geometrical arrangements of source(s) and receiver(s) as follows:

a) The simplest and most direct arrangement is a straight-line one which uses a single source and a single receiver (figure 3.10). A variation of the straight-line approach uses a single source and two receivers at different distances or a single receiver and two sources positioned at different distances from the receiver. A multiplicity of sources or receivers creates more than one baseline which extends the range of transmissivities which can be determined from the instrument readings. The first transmissometer as tested at Nantucket (See Chapter 6) was installed with two sources. However, such an arrangement is usually not satisfactory because an increase in the field of view of the receiver is required. Therefore, when a dual-baseline transmissometer was installed at the Landing Aids Experiment Station, two receivers were used, , positioned 500 and 1000 feet from the single source at the T-D location.

b) Another arrangement uses folded optics and includes one or more reflectors which "fold" the light from the source back to the receiver. Since the source and receiver can be located in close proximity to each other when using folded optics, this arrangement is frequently used where long straight-line arrangements are not feasible.

To aid in calibration or to compensate for changes in the intensity of the source, a feedback loop, consisting of immediately reflecting a small portion of the light from the source directly to the receiver, or to an auxiliary receiver, is frequently a design feature of both straight-line and folded optics arrangements. Such an arrangement is shown in figure 5.1.

5.1.2 Error Analysis - Transmissometers

Note: In the error analyses of this chapter, an atmosphere in which the transmittance does not change with position has been tacitly assumed.

5.1.2.1 Relative error in the visual range of objects

The effect of small instrumental errors in a transmissometer on the indicated visual range of objects by day may be found as follows:

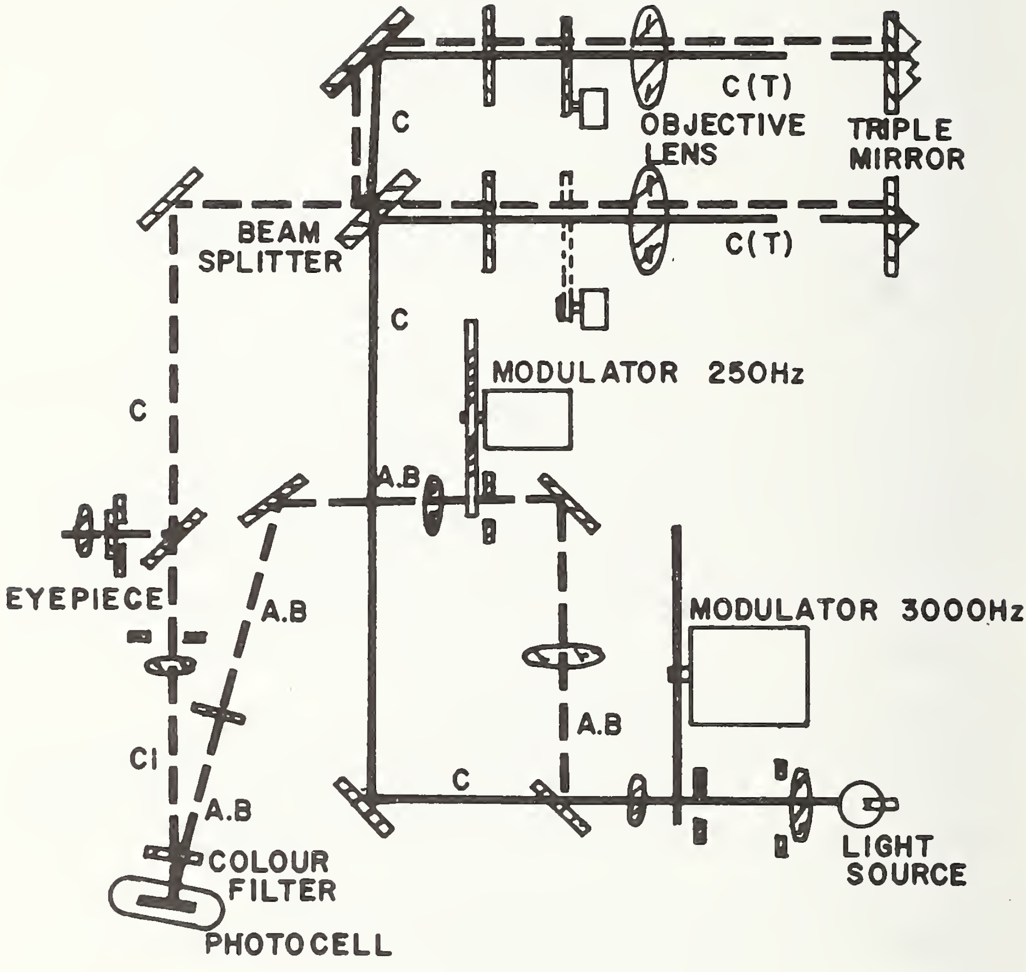


Figure 5.1 Optical diagram of Eltro dual beam transmissometer.

From Koschmieder's law (4.08) and the relation between transmissivity and transmittance (2.07)

$$\varepsilon = t_b^{V/b}. \tag{5.01}$$

If t_b' is the erroneous transmittance indicated by the instrument, then V', the erroneous visual range determined from this transmittance is given by

$$\varepsilon = t_b'^{V'/b}. \tag{5.03}$$

Let

$$t_b' = (1 + m)\, t_b$$

and

$$V' = (1 + n)\, V,$$

where m is the relative error in t_b, and n is the relative error in V.

Then

$$t_b^{V/b} = (t_b')^{V'/b},$$

or

$$t_b^{V/b} = [(1 + m)\, t_b]^{(1 + n)\, V/b}, \tag{5.04}$$

and

$$(V/b) \ln t_b = (1 + n)\,(V/b)\,[\ln (1 + m) + \ln t_b]. \tag{5.05}$$

Since, from (5.01),

$$\ln t_b = (b/V) \ln \varepsilon,$$

it is possible to substitute in (5.05) and obtain

$$\ln \varepsilon = (1 + n)(V/b)\ln(1 + m) + (1 + n) \ln \varepsilon. \qquad (5.06)$$

Equation (5.06) can then be solved, obtaining

$$n/(1 + n) = -V \ln(1 + m)/b \ln \varepsilon. \qquad (5.07)$$

If m is sufficiently small, ln (1 + m) = m, and (5.07) may be written as

$$n/(1 + n) = -mV/b \ln \varepsilon, \qquad (5.08)$$

and if n also is small, (5.08) reduces to

$$n = -mV/b \ln \varepsilon. \qquad (5.09a)$$

Since n is defined as the relative error in V and m as the relative error in t_b, (5.09a) can be rewritten as

$$\Delta V/V = -(V/b \ln \varepsilon)\ \Delta t_b/t_b, \qquad (5.09b)$$

When n and m are sufficiently small, the preceding analysis can also be made through the use of calculus.

Thus, from (5.01),

$$(V/b) \ln t_b = \ln \varepsilon. \qquad (5.10)$$

Differentiating, assuming ε is constant,

$$(\ln t_b)\ dV/b + V\ dt_b/(b\ t_b) = 0,$$

or

$$dV/V = -(1/\ln t_b)\ dt_b/t_b. \qquad (5.11)$$

Substituting for $\ln t_b$ from (5.10)

$$dV/V = -(V/b \ln \varepsilon)\ dt_b/t_b \qquad (5.12)$$

or, for small finite errors,

$$\Delta V/V = -(V/b \ln \varepsilon)\ \Delta t_b/t_b$$

which is (5.09b).

Note also that $\ln \varepsilon$ is negative. Thus a positive error in the transmittance measurement will cause a positive error in the indicated visual range.

If a value of 0.05 is assumed for ε, (5.09b) becomes

$$\Delta V/V = (V/3b)\ \Delta t_b/t_b \tag{5.13}$$

which shows that if the visual range is less than three times the length of the transmissometer baseline, the relative error in indicated visual range will be less than the error in the transmittance measurement.

5.1.2.2 Relative error in the visual range of lights

From Allard's law,

$$E_t = I\ t_b^{V/b}/V^2. \tag{5.02}$$

Rearranging terms and taking natural logarithms,

$$(V/b)\ \ln t_b = \ln (E_t/I) + 2 \ln V. \tag{5.14}$$

Differentiating, holding E_t and I constant,

$$[(\ln t_b)/b]\ dV + (V/bt_b)\ dt_b = (2/V)\ dV.$$

Rearranging terms,

$$dV/V = (V/b)(dt_b/t_b)/[2 - (V \ln t_b)/b] \tag{5.15}$$

Note that the second term in the denominator contains both V and $\ln t_b$ and that these quantities are not independent. Equation (5.15) can be put into a more useful form by substituting the righthand side of (5.14) for $(V/b) \ln t_b$ obtaining

$$dV/V = (V/b)\ [1/(2 - \ln(E_t/I) - 2 \ln V)]\ dt_b/t_b. \tag{5.16}$$

Then, for small finite errors

$$\Delta V/V = (V/b)\ [1/(2 - \ln(E_t/I) - 2 \ln V)]\ \Delta t_b/t_b, \tag{5.17}$$

where $\Delta V/V$ is the error in the indicated visual range corresponding to a relative error in the transmissometer $\Delta t_b/t_b$.

Comparing (5.17) with (5.12) shows that the two equations are the same except that the term $-1/\ln \varepsilon$ in (5.12) has been replaced by $1/(2 - \ln(E_t/I) - 2 \ln V)]$. The effect of this change is illustrated by the following.

Note that if T is equal to one (perfectly clear weather), (5.02) reduces to

$$E_t/I = 1/V^2 \quad \text{(inverse square law)},$$

and

$$\ln (E_t/I) = -2 \ln V. \tag{5.18}$$

The maximum possible value of the visual range, V, can be determined by combining (5.18) and (5.17). When V is near this value

$$\Delta V/V = (V/2b)\ \Delta t_b/t_b. \tag{5.19}$$

Comparing (5.19) and (5.13) shows that, in clear weather, the effects of instrumental errors on the visual range of lights is somewhat greater than on the visual range of objects.

As an example of the effect of instrumental errors during conditions of restricted visibility assume:

> Illuminance threshold, E_t, of 2 mile candles (7.17×10^{-8} footcandle); (nighttime conditions),
>
> source intensity, I, of 10,000 candelas, and
>
> transmissometer baseline of 500 feet.

Then from (5.17), since, when the foot is used as the unit of length,

$$\ln E/I = -25.66$$

$$\Delta V/V = (V/500)\ [1/(27.66 - 2 \ln V)]\ \Delta t_b/t_b.$$

Let F, the error factor, be defined as

$$F = 1/(27.66 - 2 \ln V). \tag{5.20}$$

Then

$$\Delta V/V = (FV/b)\ \Delta t_b/t_b. \tag{5.21}$$

Table 5.1 has been computed from (5.20) using the assumptions given above.

TABLE 5.1

Transmissometer Error Factor for a 500 Foot Baseline Transmissometer, Nighttime Conditions

Visual Range, V (feet)	Error Factor, F	FV/b
500	0.066	0.066
1000	.072	.14
2000	.080	.32
5000	.094	.94
10000	.108	2.2

Table 5.2 has been computed, similarly, for daytime conditions assuming a threshold illuminance of 1000 mile candles (3.59×10^{-5} footcandles).

TABLE 5.2

Transmissometer Error Factor for a 500 Foot Baseline Transmissometer, Daytime Conditions

Visual Range, V (feet)	Error Factor, F	FV/b
500	0.11	0.11
1000	.13	.26
2000	.16	.64
5000	.23	2.3
10000	.33	6.6

These tables illustrate the very small effect that transmissometer instrument errors have on the visual range of high intensity lights during conditions of restricted visibility, especially at night.

Note that for objects the error factor is $1/\ln \varepsilon$, and if a contrast threshold of 0.05 is assumed, the error factor for objects becomes 0.3 for all visual ranges.

5.1.2.3 Choice of Baseline

The preceding analysis shows that the percentage error in the visual range indicated by the instrument is directly proportional to the relative instrumental error and to the true visual range and inversely proportional to the distance between the light source and the receiver. It is evident that if the error in the indicated visual range is to be kept small for large visual ranges, either the instrument must be very accurate, so that $\Delta t_b/t_b$ is small, or the distance b, between the source and the receiver, must be an appreciable fraction of V, the visual range. Thus, error analysis also plays a role in the choice of a baseline for a transmissometer system, i.e., the distance traversed by the beam from the lamp to the telephotometer. Equations (5.13) and (5.21) indicate the desirability of making the length of the baseline as long as possible. The limiting factor is the minimum transmittance, t_b, which is to be measured.

It can be easily shown from (2.08) that the maximum length of a transmissometer baseline is given by

$$b = \ln t_m / \ln T_m \tag{5.22}$$

where

b is the length of the baseline,

T_m is the minimum transmissivity to be measured, and

t_m is the minimum transmittance which can be measured by the instrument.

As an example, assume that a transmissometer is to be used to indicate runway visual ranges down to 1000 feet; that these ranges are based upon an intensity of 10,000 candelas; that the illuminance threshold is 2 mile candles (since nighttime is the limiting case); and that the instrument can operate down to a transmittance of 0.001.

Using the assumptions given above, converting b to miles to keep the units consistent, and rewriting (5.14), using common logarithms, a value of -27.2 is obtained for log T (per mile). Note that common logarithms are used here because of their convenience when using nomograms of Appendix C to compute visual ranges.

Thus

$$b = -3/-27.2 = 0.11 \text{ miles},$$

or

$$b = 580 \text{ feet}.$$

Similarly for an RVR of 500 feet, (0.095 mile)

$$\log T = -61,$$

and

$$b = 0.049 \text{ mile} = 260 \text{ feet}.$$

In keeping with this principle, the baselines of the first transmissometers installed for operational use at civil airports used a 750 foot baseline. This was later reduced to 500 feet when Category II operations, having an RVR minimum of 1200 feet, were started. Now, with the advent of Category III operations, a 250 foot baseline is being used.

Errors in reported RVR will result if the transmissometer's actual baseline length differs from the specified baseline distance used by the "computer" in RVR computations. On some occasions, a transmissometer system must be installed with a baseline differing slightly from the specified baseline because physical obstructions prevent the baseline from being laid out to its exact nominal length. The errors in daytime RVR can be found from Koschmieder's Law,

$$\varepsilon = t_b^{V/b}. \qquad (5.01)$$

If b' is the baseline used, then V', the computed visual range, is given by

$$\varepsilon = t_{b'}^{V'/b} \qquad (5.31)$$

Combining (5.01) and (5.31)

$$t_b^{V/b} = t_{b'}^{V'/b},$$

and

$$V/b \ln t_b = V'/b \ln t_{b'} . \qquad (5.32)$$

Since $\quad t_b' = t_b^{\,b'/b}$,

(5.32) reduces to

$$V' = Vb/b', \qquad (5.33)$$

and

$$\frac{\Delta V}{V} = \frac{-\Delta b}{b'} . \qquad (5.34)$$

Therefore the relative error in the indicated visual range by day is equal to the relative error in the length of the baseline, but opposite in sign.

The errors by night will be less, due to the compensating effects of the inverse square aspects of Allard's Law.

5.1.2.4 Instrumental Determination of Transmissometer 100% Setting.

The most significant source of error in a well designed transmissometer is in the adjustment of the sensitivity of the instrument. In transmissometers, this error is apparent as an error in the 100% setting, that is, the transmittance which would be indicated were the air perfectly clear. There are four basic instrumental methods of calibrating a transmissometer to obtain the 100% setting.

a. By separate measurement of the intensity of the source and the sensitivity of the receiver and adjustment of the intensity or sensitivity to obtain an instrument reading of 1.00 with no attenuation losses. Experience on the outdoor photometric range at the National Bureau of Standards indicates that using this method, even with careful photometry, errors in the 100% setting may be as large as 5%. This method is not readily applicable to field conditions.

b. By measurement of the illuminance produced by the transmissometer light source with a receptor having a stable, but unknown, sensitivity at the receiver and at a position near the source and computing the transmittance from these measurements. A uniform and stable transmittance over the transmissometer baseline is assumed. Field tests by NBS at Arcata indicate that calibrations can be made in relatively clear weather (meteorological visibility above 5 miles) with expected errors of about 2% [29]. See Section 6.2.2.

Note: The distance between the transmissometer source and the nearer position of the receptor must be sufficiently large to insure that the illuminance from the source follows the inverse square law.

c A variant of method (b) utilizes the very narrow-beam properties of a laser [75]. If a laser is used as a source, it is possible to construct a portable receptor which, when located at the transmissometer receiver, will intercept the entire beam of a laser located at the transmissometer light source. The prevailing transmittance is then the ratio of the flux incident on the portable receptor when it is at the transmissometer receiver to the flux incident on the receptor when it is immediately in front of the laser source. Such calibrators have been constructed, but their accuracy is not known. This method is, in principle, independent of the visibility prevailing at the time of calibration. However, its accuracy under conditions of poor visibility is limited by the accuracy with which the output meters of the calibrator and the transmissometer can be read. Moving pointer indicators, of the type used in the transmissometer, can be read to about one-quarter of a scale division or, with a typical meter having 50 scale divisions, to about 0.005 units. Thus, if the prevailing transmittance were 0.20, the uncertainty in reading the transmittance would be 4%, assuming no linearity or zero correction errors.

d. Use of a stable portable instrument which can be installed on the transmissometer stands and aligned easily under conditions of poor, as well as of good, visibility. The problems of setting accuracy discussed in (c) apply here also.

5.1.2.5 Visual Estimate Calibration.

Another method of obtaining a 100% setting is by the visual estimation of meteorological visibility and subsequent adjustment of the transmissometer to obtain a reading equal to the transmittance corresponding to the estimated object visibility. The accuracy of the setting depends upon the length of the baseline and the prevailing meteorological visibility as well as upon the uniformity of the atmosphere. This is the method most frequently used.

5.1.2.6 Errors in the Visual Estimate Calibration.

The relative error in transmittance resulting from the visibility estimate of this method may be computed as follows:

Let V_o be the "true" visibility, that is, the visibility representative of the transmittance over the transmissometer baseline and let V_e be the visibility estimated by the observer. Then the "true" transmittance, t_o*, is given by the relation

$$t_o^{V_o/b} = \varepsilon, \qquad (5.23a)$$

and the estimated transmittance, t_e, is given by the relation

$$t_e^{V_e/b} = \varepsilon. \qquad (5.23b)$$

If 'a' is the relative error in transmittance,

$$t_e = (1 + a)\, t_o. \qquad (5.24)$$

Combining equation (5.23a) and 5.23b)

$$t_e/t_o = \varepsilon^{(b/V_e - b/V_o)},$$

and from (5.24)

$$a = \varepsilon^{(b/V_e - b/V_o)} - 1. \qquad (5.25)$$

If the quantity $(b/V_e - b/V_o)$ is small, less than about 0.1, (5.25) may be expressed as

$$a = (b/V_e - b/V_o) \ln \varepsilon. \qquad (5.26)$$

The error in transmittance will be not more than 3% with a 500-foot baseline transmissometer (1.5% for a 250-foot baseline

*The subscript b is omitted throughout this development.

instrument) if the transmittance over the transmissometer baseline is that corresponding to a visibility of 5 miles or more, and the transmissometer is adjusted as though the transmittance were representative of a visibility of 10 miles. The error would be 6% for a 500-foot instrument (3% for a 250-foot instrument) if for all visibilities above 2.5 miles the transmissometer were adjusted as though the transmittance over its baseline corresponded to a visibility of 5 miles.

5.1.2.7 Analysis of the Effects of Errors in the Visual Estimate Calibration.

The effects of errors in the 100% setting on other visibilities indicated by the transmissometer as a function of transmittance and visibility may be computed on the basis of the visual range of objects as follows. (Because of the effects of the inverse square law, the errors in the indicated visual range of lights will be less than those for objects. See Section 5.1.2.2.)

Let V be the visibility which would be obtained if the 100% setting of the transmissometer were correct and let t_b be the corresponding transmittance over the baseline b, and let V' be the indicated visibility as a result of an incorrect 100% setting and t'_b be the corresponding transmittance over the baseline b. Then, if from (5.03)

$$t_b' = (1 + a)\, t_b,$$

$$(V/b) \ln t_b = (V'/b)\, [\ln t_b + \ln (1 + a)]. \qquad (5.27)$$

The relative error in visibility is then given by

$$(V' - V)/V = \Delta V/V = -\ln(1 + a)/[\ln t_b + \ln(1 + a)]. \quad (5.28)$$

If 'a' is small,

$$\ln(1 + a) = a,$$

and

$$\Delta V/V = -a/(\ln t_b + a). \qquad (5.29)$$

By using either of equations (5.28) or (5.29), it is possible to compute the maximum transmittance for which the error in indicated visibility will be less than a stated tolerable error as a function of the error in the 100% setting. The results of such a computation using equation (5.28) are given in table 5.3. If equation (5.29) had been used the maximum transmittance shown would have been slightly (less than 0.01) lower. Note that $\Delta V/V$ and 'a' have the same sign.

TABLE 5.3

Maximum Permissible Transmittance

Tolerable Relative Error in Visibility	Relative Error Present in Transmittance Reading	Maximum Permissible Transmittance (1)
0.05	0.01	0.81
	.02	.66
	.05	.36
	.10	.14
0.10	0.01	0.90
	.02	.80
	.05	.58
	.10	.35
0.20	0.01	0.94
	.02	.89
	.05	.75
	.10	.56

(1) At which the error in visibility produced by the error in 100% setting shown in Column 2 is less than the tolerable error shown in Column 1.

For typical values of 'a' and for values of V less than of the order of ten times the baseline, equation (5.12) applies. It may be written

$$\Delta V/V = -aV/(b \ln \varepsilon), \qquad (5.30a)$$

since

$$a = \Delta t_b/t_b.$$

If an error in transmittance of 2% and a contrast threshold of 0.05 are assumed,

$$\Delta V/V = 0.007\ V/b \qquad (5.30b)$$

It is apparent from the figures given above, that, if the transmittance over the transmissometer path is representative of the prevailing transmittance, errors in the estimation of visibility during a transmissometer calibration will have a small effect on the accuracy of the indicated visibility by the transmissometer during periods of low visibility. Experience has shown that spatial non-uniformity in atmospheric transmittance is the greatest source of error in the 100% setting. The effects of non-uniformity can be reduced significantly by using records of transmittance and visibility reports extending over a period of hours, or days if possible.

Note that discussion has been based upon the visual range of objects. The relative errors in the visual range of lights, as shown earlier, will usually be less than that for objects.

5.1.3 Scattered Light Error in Transmissometers.

A very important consideration in the accuracy of a transmissometer is the extent to which it measures the regular transmittance of the atmosphere.

In a fog, a telephotometer such as the transmissometer receiver will receive, in addition to the light which passes directly from the source to the receiver, some additional light which, although radiated from the source, would not reach the receiver in clear weather. This scattered light constitutes an error in the transmittance measurement.* In dense fogs this error may become large, especially when the size of the fog droplets is small. In the NBS transmissometer, the error is minimized by keeping the field of view of the receiver and the beam spread of the projector as small as possible.

*For an extensive treatment of theoretical aspects of the effects of scatter on measurements of atmospheric attenuation, see the study by Höijer [45].

In the 1950's, NBS conducted extensive experiments at Arcata, under the direction of John W. Simeroth, to determine the errors introduced in transmissometer measurements by scattered light, the results of which are previously unpublished. Two transmissometers were installed on parallel 500-foot baselines 20 feet apart. In the initial setup, baffles were installed along the line-of-sight of one instrument to restrict the light beam and further restrict the field of view of the receiver, thereby reducing the effects of scattered light on this instrument. This configuration would allow the direct comparison of transmittance measurements consisting, essentially, only of directly transmitted light with those consisting of directly transmitted light plus any increase in the measurement due to scattered light. This method requires very accurate measurements of transmittance, since the scattered light component of the measurement may be small, and is dependent on both instruments measuring portions of the atmosphere which are identical in density and homogeneity. However, the terrain in the vicinity of this instrument, although without large or sudden changes in the contour, was such that even slight winds had a considerable effect on the homogeneity of the fog with the result that the measurements were unreliable and sometimes the baffled instrument actually indicated higher transmittance than the unbaffled instrument (it should always be lower). An indirect method was therefore adopted.

One transmissometer, well-baffled, was used to measure as nearly as possible the direct transmittance. The baffling of this instrument consisted of five 4-foot square baffles located at distances of 6, 8, 54, 162, and 486 feet from the projector having aperture diameters of 9, 9, 9, 7, and 4.5 inches. The other transmissometer, unbaffled, with a 6-inch disc midway between the projector and receiver to occlude all directly transmitted light, measured only the scattered light, i.e., the error that is introduced into measurements made with an unbaffled transmissometer.

The disc was removable to check the 100% calibration. The arrangement is shown in figure 5.2. Measurements of the scattered light and regularly transmitted light were made simultaneously.

The standard transmissometer lamp is a 120-watt, 6-volt, PAR-64 type having a C-6 filament. Initial output is approximately 180,000 candelas peak beam candlepower with a 2.5° horizontal, 5° vertical beam spread, measured at 50% of peak intensity. The filament was so shielded that no direct light from it was emitted by the lamp.

During some of the measurements, a partially shielded bare lamp was used. This lamp was a 5-kilowatt, 120-volt, T-64 type having a C-13 planar filament. The shield consisted of a cylinder, 24 inches in diameter, placed over the lamp with its upper edge level with the lower edge of the filament. The lamp was completely unshielded in the upper hemisphere and had an approximately hemispherical distribution.

The disc used on the unbaffled transmissometer unavoidably obscurred that small portion of scattered light due to scattering which takes place near the line of sight between the source and the edge of the baffle. Also, the scattered light measurement contained a component resulting from diffraction around the disc baffle. To determine which corrections should be made for the effects of the disc baffle, the ratio of scattered to regularly transmitted light, $\Delta t/t$, was plotted as a function of receiver half-angle field of view for six different atmospheric conditions. According to geometrical optics, if only first order scattering is considered, the ratio $\Delta t/t$ should approach zero as the angular field of the receiver is decreased to equal that angle subtended at the receiver by the disc. As shown on figure 5.3, the ratio becomes zero at a half-angle field of view of 1 milliradian. If it were possible to measure scattered light error without discs or baffles, the lines on figure 5.3 would all intersect at the point $\Psi = 0$, $\Delta t/t = 0$. Therefore the y intercept shown is the correction that must be applied for the indicated transmittance.

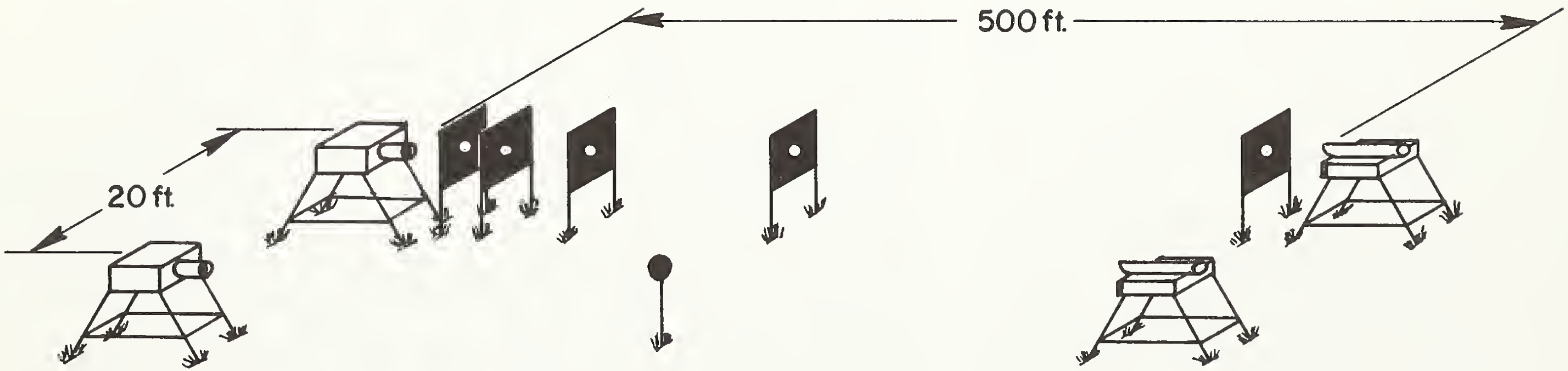


Figure 5.2 Arrangement of two transmissometers installed at Arcata on parallel 500 foot baselines 20 feet apart. Upper baffled transmissometer measures direct transmittance. Lower transmissometer measures light scattered around disc located midway between the projector and receiver.

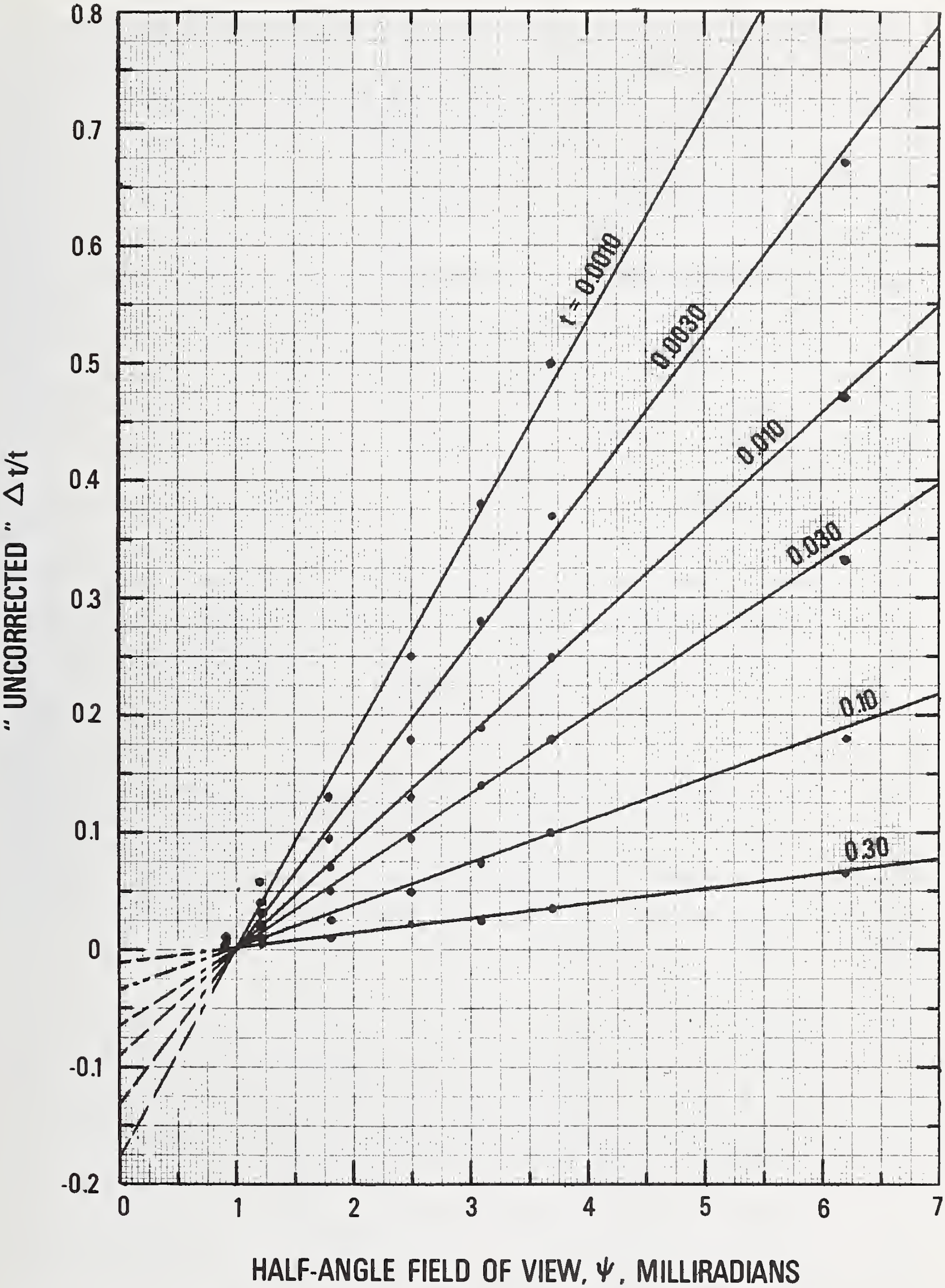


Figure 5.3 Some of the curves used in determining correction values due to disc baffle using the transmissometer projector as a light source. Note that 6" baffle subtends angle of 1 milliradian at receiver.

Figure 5.4 shows the correction, as a function of transmittance, that must be applied in correcting for the effects of the disc baffle.

The curve in figure 5.4 was obtained by plotting the adjustments (increases) in $\Delta t/t$, for each transmittance, required to make all of the lines in figure 5.3 pass through the point $\Psi = 0$, $\Delta t/t = 0$. The curve in figure 5.4 shows the amount that $\Delta t/t$ must be increased, for a particular transmittance, to correct the scattered light measurements for the effects of the disc baffle, when the source is the regular transmissometer lamp. These corrections apply regardless of the field of view of the receiver, since the phenomena is due solely to the disc baffle.

Figures 5.5 and 5.6 show the ratio, $\Delta t/t$, plotted as a function of transmittance for seven different half-angle fields of view. The source for the data shown in figure 5.5 was the transmissometer projector while the source for the data shown in figure 5.6 was the partially shielded bare lamp. The data show that the errors due to scattered light are dependent upon both the beam spread of the light source and the field of view of the receiver. A comparison of the curves on figures 5.5 and 5.6 shows that over the transmittance range 0.0001 to 0.01, and with a half angle field of view of 6.2 milliradians, the ratio $\Delta t/t$ is approximately 67% greater with the partially shielded lamp than with the standard transmissometer lamp. When the half angle field of view is reduced to 1.2 milliradians, the standard opening for the 500 foot transmissometer receiver, the increase in $\Delta t/t$ drops to 36% at a transmittance of 0.0001 and 42% at 0.01.

A few measurements were made with the shield removed from the bare lamp. Under these conditions, and at a transmittance of about 0.00025, the error for the bare lamp was about 4 times that obtained using the standard transmissometer lamp. Not many unshielded bare lamp measurements were taken due to the "ground factor" - an unknown quantity of light is reflected from the ground surface toward the receiver. The unknown ground factor was considered too high to make continuation of these measurements useful.

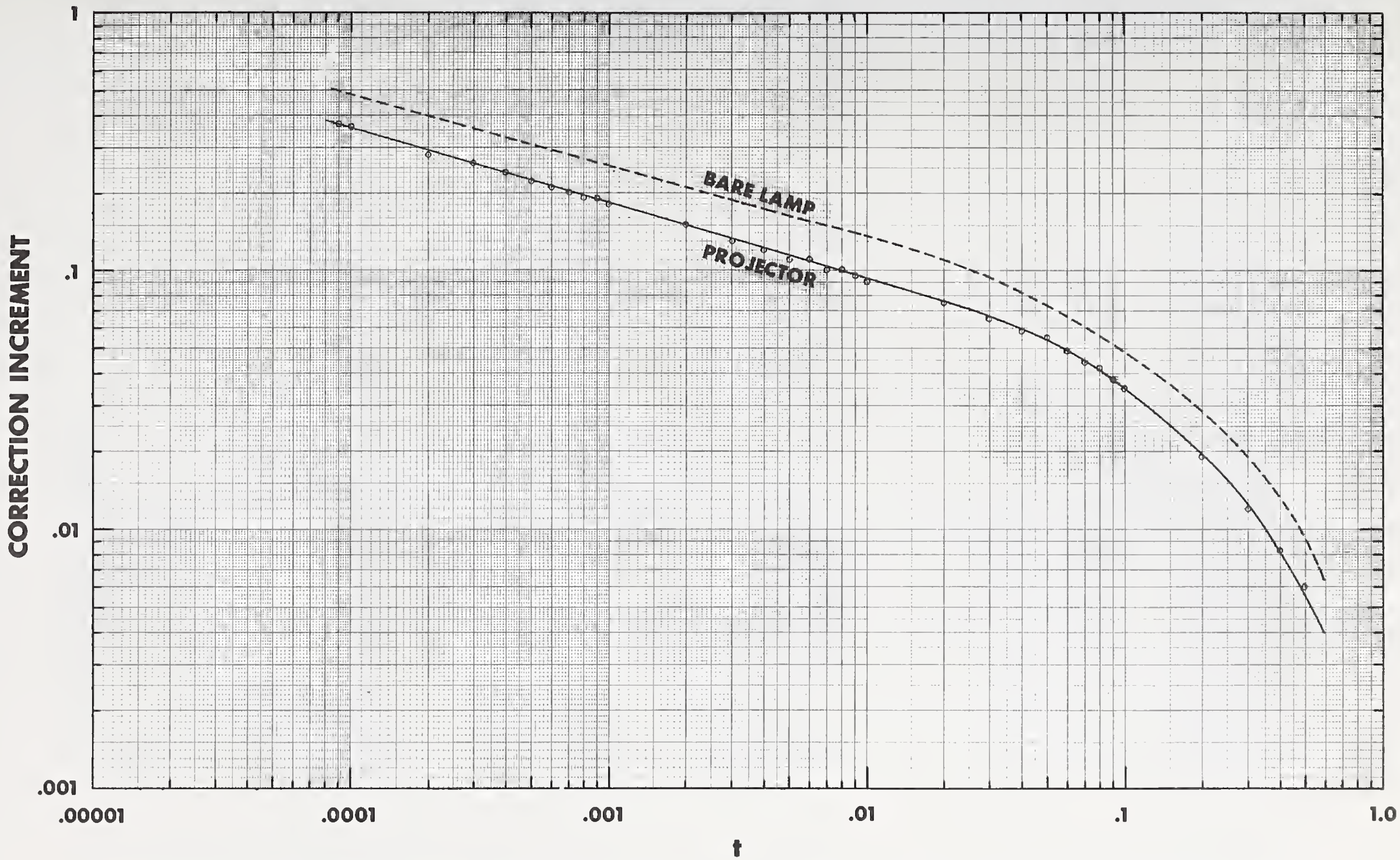


Figure 5.4 Corrections for effects of disc baffle, which were applied to the scattered light error, $\Delta t/t$, as a function of the transmittance, t. The corrections apply regardless of receiver field of view.

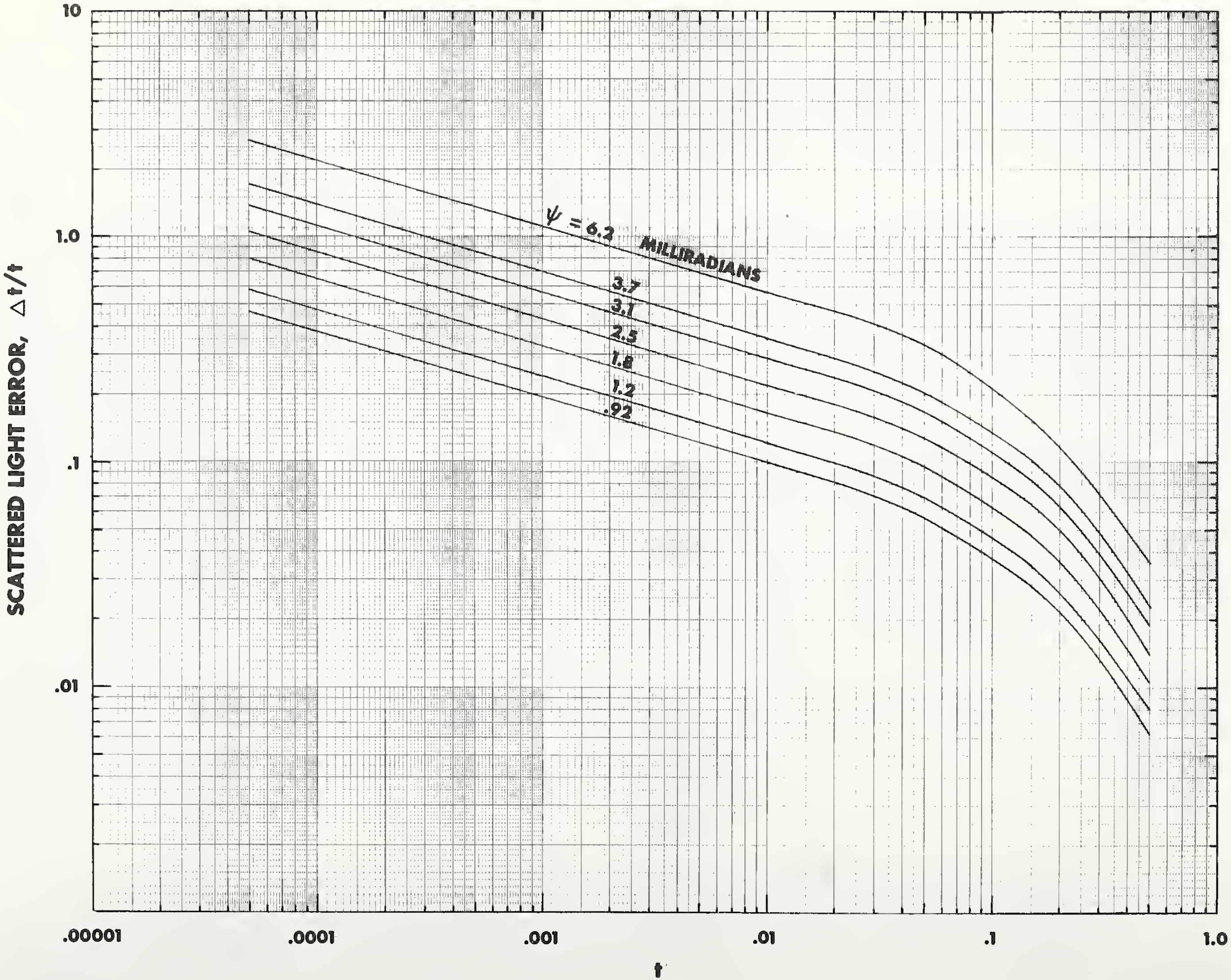


Figure 5.5 The scattered light error, Δt/t, corrected for effects of disc baffle, plotted as a function of true transmittance, t, for different receiver half-angle fields of view. The source is a transmissometer projector. The baseline is 500 feet.

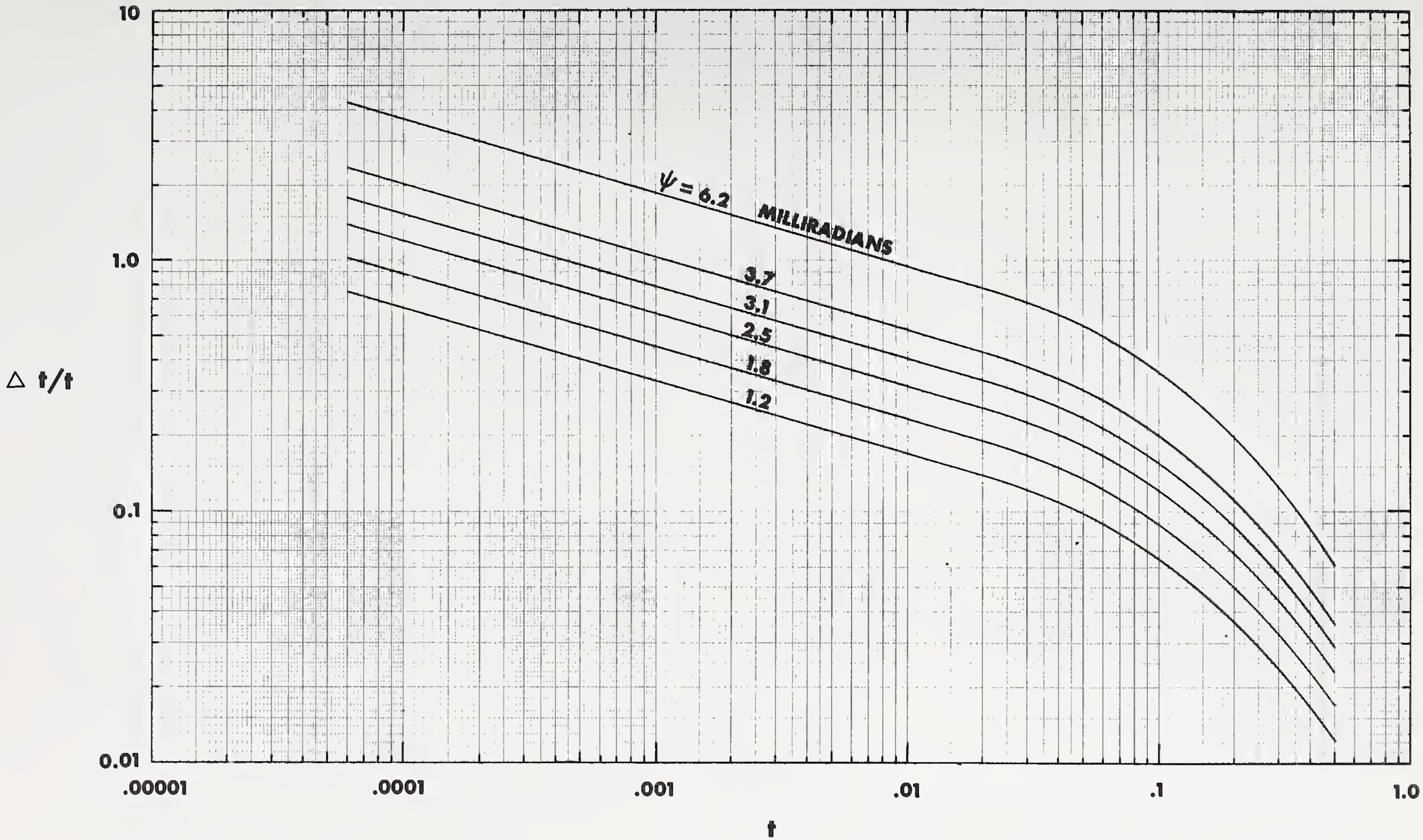


Figure 5.6 The scattered light error, $\Delta t/t$, corrected for effects of disc baffle, plotted as a function of true transmittance, t, for different receiver half-angle fields of view. The source is a partially shielded bare lamp. 500-foot baseline.

The errors in relative transmittance shown on figure 5.5 are summarized in table 5.4.

Table 5.4

"Scattered Light" Error in Transmittance Measurements
(For 500-foot baseline transmissometer)

Receiver Field of View (Milliradians)*	0.92	1.2	1.8	2.5	3.1	3.7	6.2
"True" Transmittance	Percent Error in Transmittance (100 Δt/t)						
0.5	0.6	0.8	1.1	1.4	1.9	2.3	3.6
0.1	3.7	4.6	6.0	7.5	11	14	21
0.01	10	12	16	22	29	35	56
0.001	19	24	32	43	57	70	110
0.0001	38	47	64	85	110	140	220

*Half-cone angle

The errors shown are average values. Frequently there was considerable variation in the relative transmittance error from fog to fog with these errors ranging from about half to twice the average errors given in table 5.4. The half-angular field of view of the in-service 500-foot baseline transmissometer with a 2.0 mm field stop in the receiver is 1.2 milliradians. The half-angular field of view of an in-service 250-foot baseline transmissometer with a 3.5 mm field stop is 2.2 milliradians. The errors given in table 5.4, column 5 (2.5 milliradians) are representative of the errors which would be obtained with a 250-foot baseline transmissometer where the transmittances given in column 1 are considered as the transmittance over 250 feet.

The effects of the errors shown in table 5.4 on the day visibility computed using Koschmieder's law are shown in table 5.5.

Table 5.5

Error in Indicated Visibility (Day) Resulting from "Scattered Light" Error in Transmissometer Measurements (For a 500-foot baseline transmissometer)

Receiver Field of View (Milliradians)*		0.92	1.2	1.8	2.5	3.1	3.7	6.2
"True" Transmittance	Visibility (V) (feet)	Percent Error in Indicated Visibility (100 ΔV/V)						
0.5	2092	0.9	1.2	1.6	2.0	2.8	3.4	5.4
0.1	630	1.6	2.0	2.5	3.2	4.7	6.0	9.0
0.01	315	2.1	2.5	3.3	4.5	5.8	7.0	10.7
0.001	210	2.6	3.2	4.2	5.5	7.0	8.3	12.0
0.0001	157	3.6	4.4	5.7	7.2	8.8	10.5	14.4

*Half-cone angle

The errors shown in the column headed 1.2 milliradians are applicable to a 500-foot baseline transmissometer with a 2.0 mm field stop in the receiver. Representative errors for a 250-foot baseline transmissometer may be obtained from the column headed 2.5 milliradians if the visibilities shown in the second column are halved. The transmittances in the first column are then the transmittances over a 250-foot baseline.

Note that for a given visibility (not transmittance) the relative errors in visibility for 500- and 250-foot baseline transmissometers are not significantly different. Note also that at low transmittances, although the relative errors in transmittance become large even for small angular fields of view, the relative errors in visibility for small angular fields of view are acceptable. For a given transmittance the relative error in night visibility or in day or night RVR is less than, or equal to, the relative error in daylight visibility.

Two different detectors were used during the scattered-light measurements. The phototube normally used in the transmissometer receiver has an S-1 photocathode, which is red-sensitive.

Measurements were also made with a phototube having an S-4 surface, which is blue-sensitive, to determine if any effects are due to spectral sensitivity. These results are shown in figures 5.7 and 5.8 plotted as a function of transmittance. There is negligible difference produced by the difference in spectral sensitivity.

As shown by these results, the amount of scattered light increased as transmittance decreased, reached a maximum, and then decreased as transmittance continued to decrease whereas $\Delta t/t$ increases continuously as the transmittance decreases.

Middleton also investigated the effects of scattered light, both theoretically and experimentally, for systems involving a projector and receiver [91]. Making certain assumptions, he calculated the ratio of measured illuminance for four different sets of conditions, depending on droplet radii, droplet density, and distance between source and receiver (baseline). His theoretical results are shown in figure 5.9 as a function of receiver aperture half-angle Ψ. The conditions for the three cases illustrated differ only in baseline length. θ is the source beam spread half-angle.

The predicted errors were so large that Middleton checked his results experimentally. Measurements were made at two periods during a single dense fog with a visual range of about 125 meters. The results, figure 5.10, show error as a function of receiver field of view. The error is about 5 times that calculated for Case I, probably because of a preponderence of smaller droplets. Middleton suggests that a series of baffles would be necessary in any permanent installation of a transmissometer to eliminate error due to scattered light.

A comparison of the scattered light errors obtained by Middleton with those obtained by NBS at Arcata reveals significant differences, as illustrated on figure 5.11. The higher values obtained by Middleton can be partially explained as follows:

a) There is no indication that Middleton corrected for background luminance. NBS turned off the projector and took direct

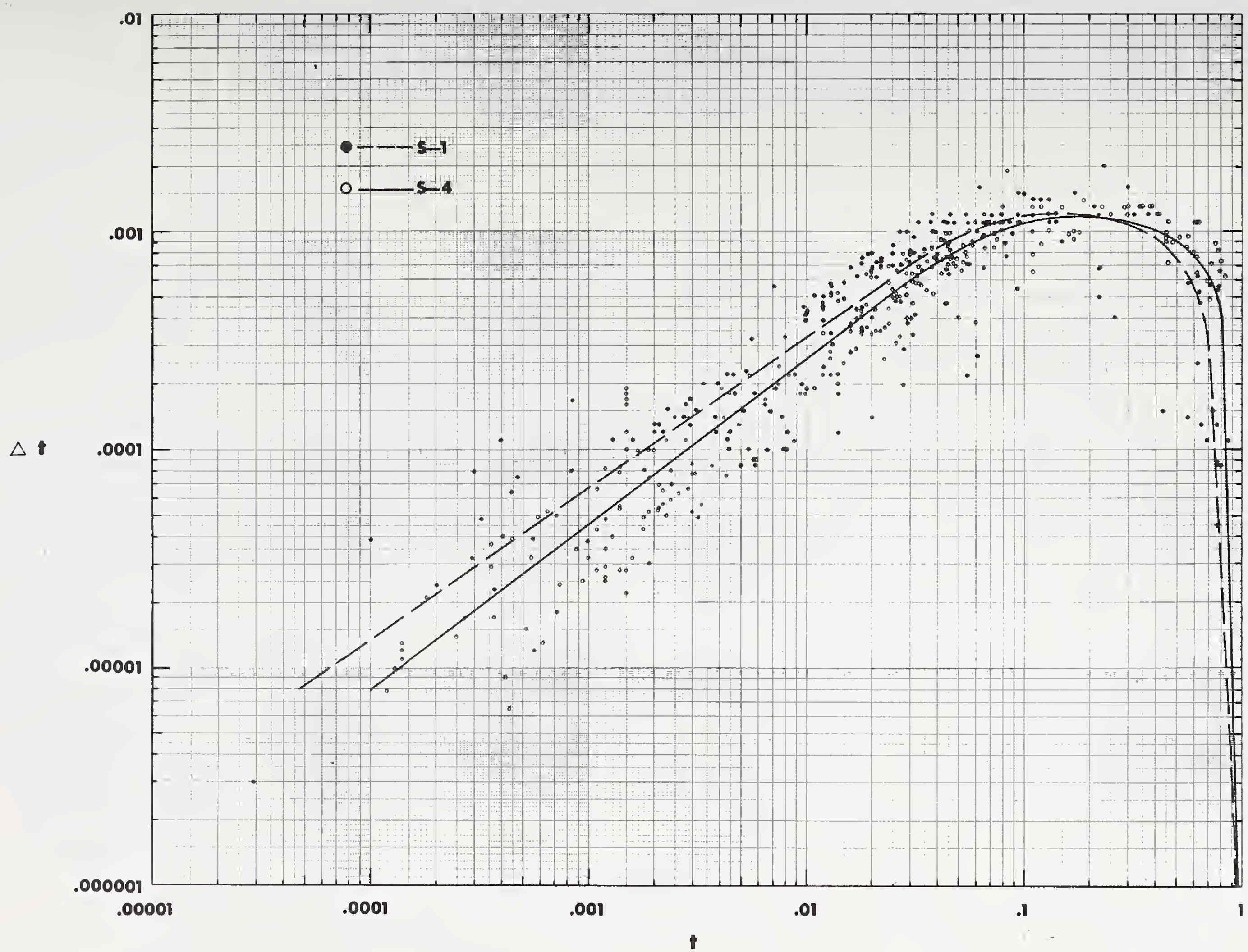


Figure 5.7. Scattered light increment, Δt, plotted as a function of transmittance, t, for red-sensitive S-1 and blue-sensitive S-4 phototubes (not corrected for effects of disc baffle). Field of view of receiver ($2\ \Psi$) is 2.5 milliradians; transmissometer projector used as source. 500-foot baseline.

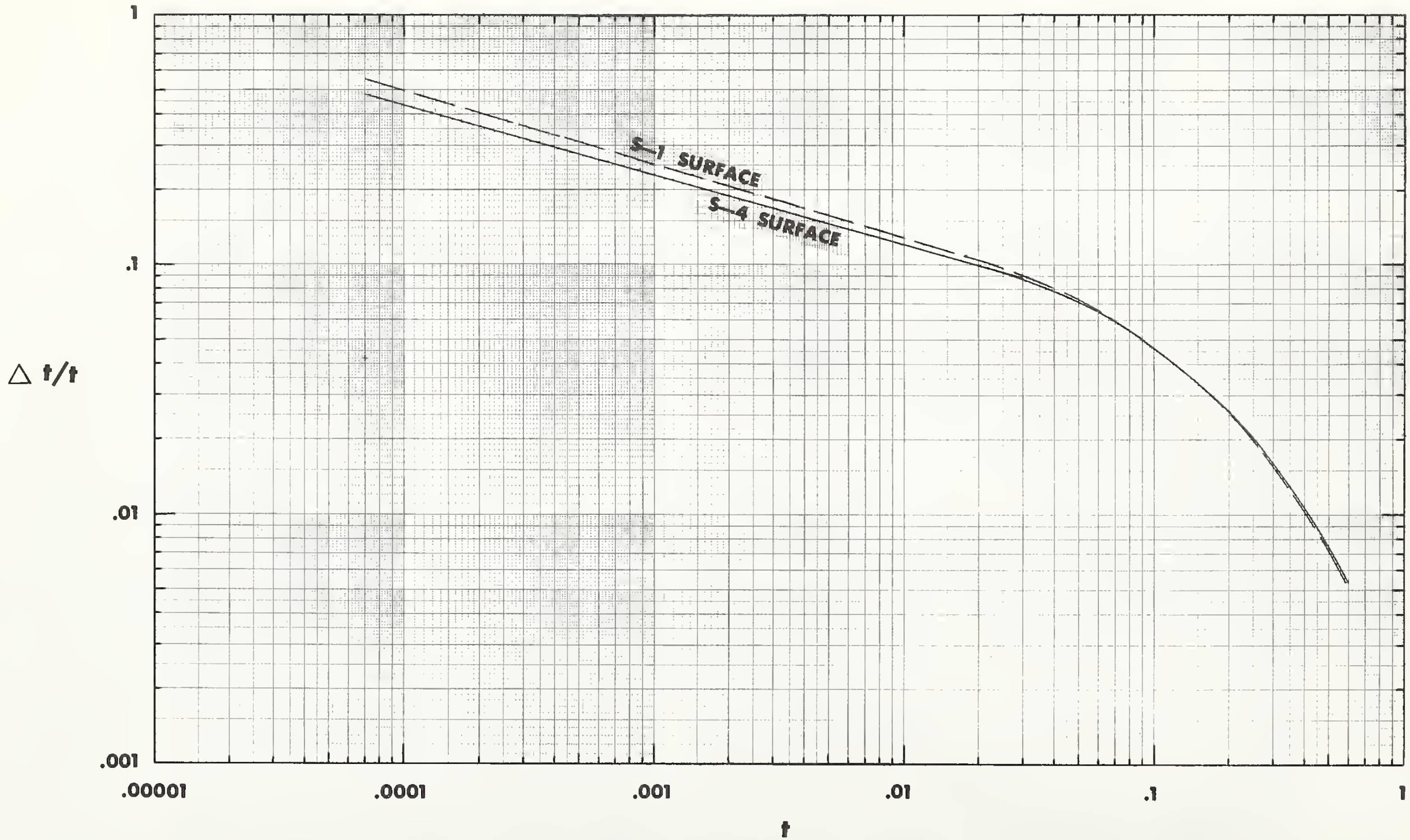


Figure 5.8. Scattered light error, Δt/t, as a function of transmittance, t, for red-sensitive S-1 and blue-sensitive S-4 phototubes. Field of view (2 Ψ) = 2.5 milliradians; transmissometer projector used as source. 500-foot baseline.

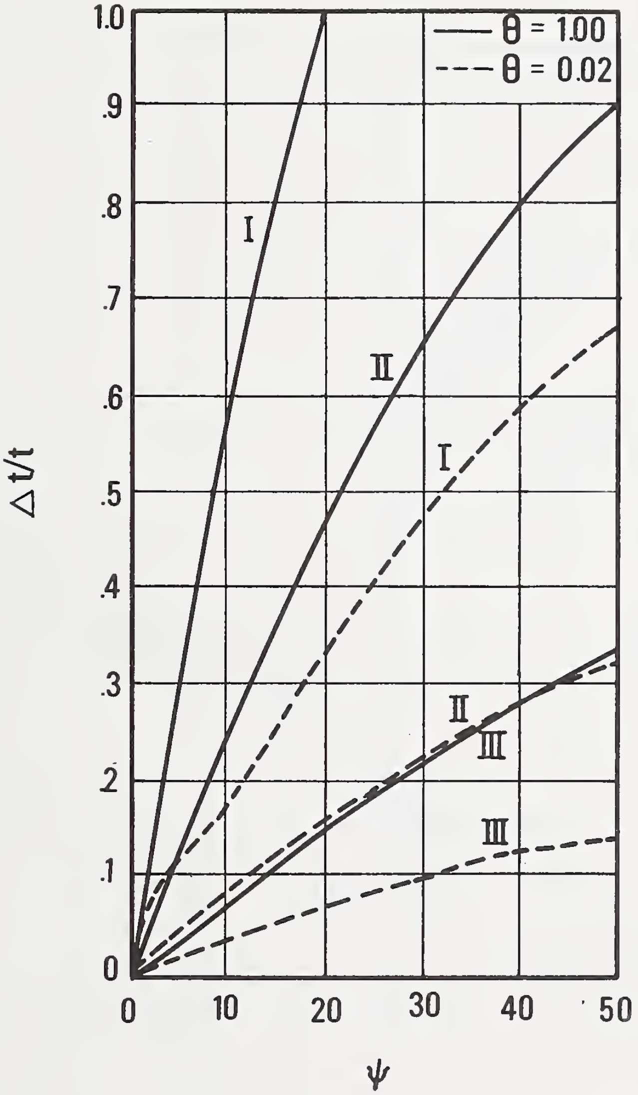


Figure 5.9 Scattered light error, $\Delta t/t$, predicted by Middleton as a function of receiver aperture half-angle ψ for source aperture half-angle θ where ψ is expressed in milliradians and θ is in radians. Cases I, II, and III differ only in baseline lengths which are 1000, 500, and 200 meters. After Middleton [91].

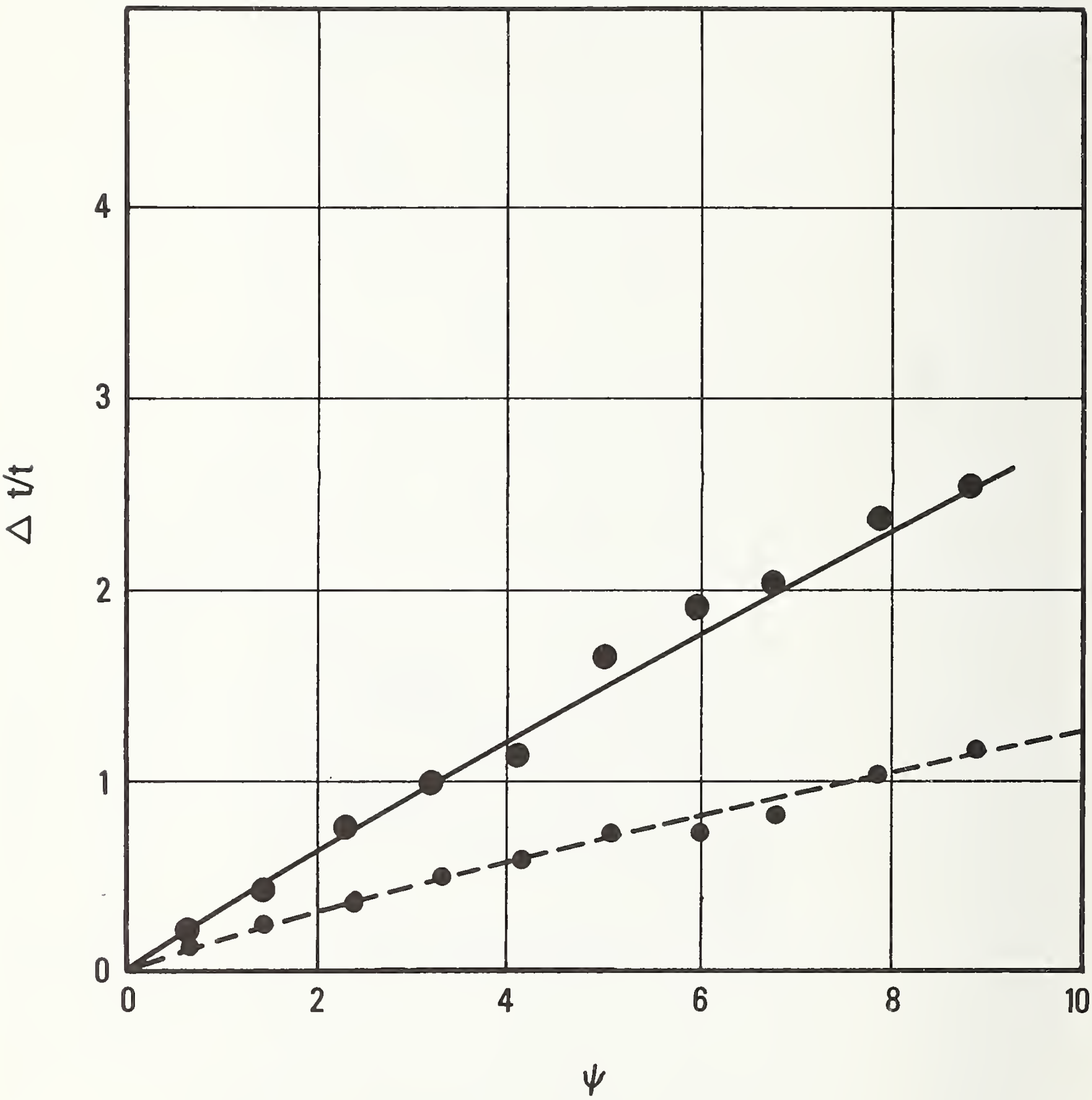


Figure 5.10 Experimental values of the scattered light error, Δt/t, as determined by Middleton at two periods in a single fog. θ = 0.30 radians. ψ in milliradians. After Middleton [91].

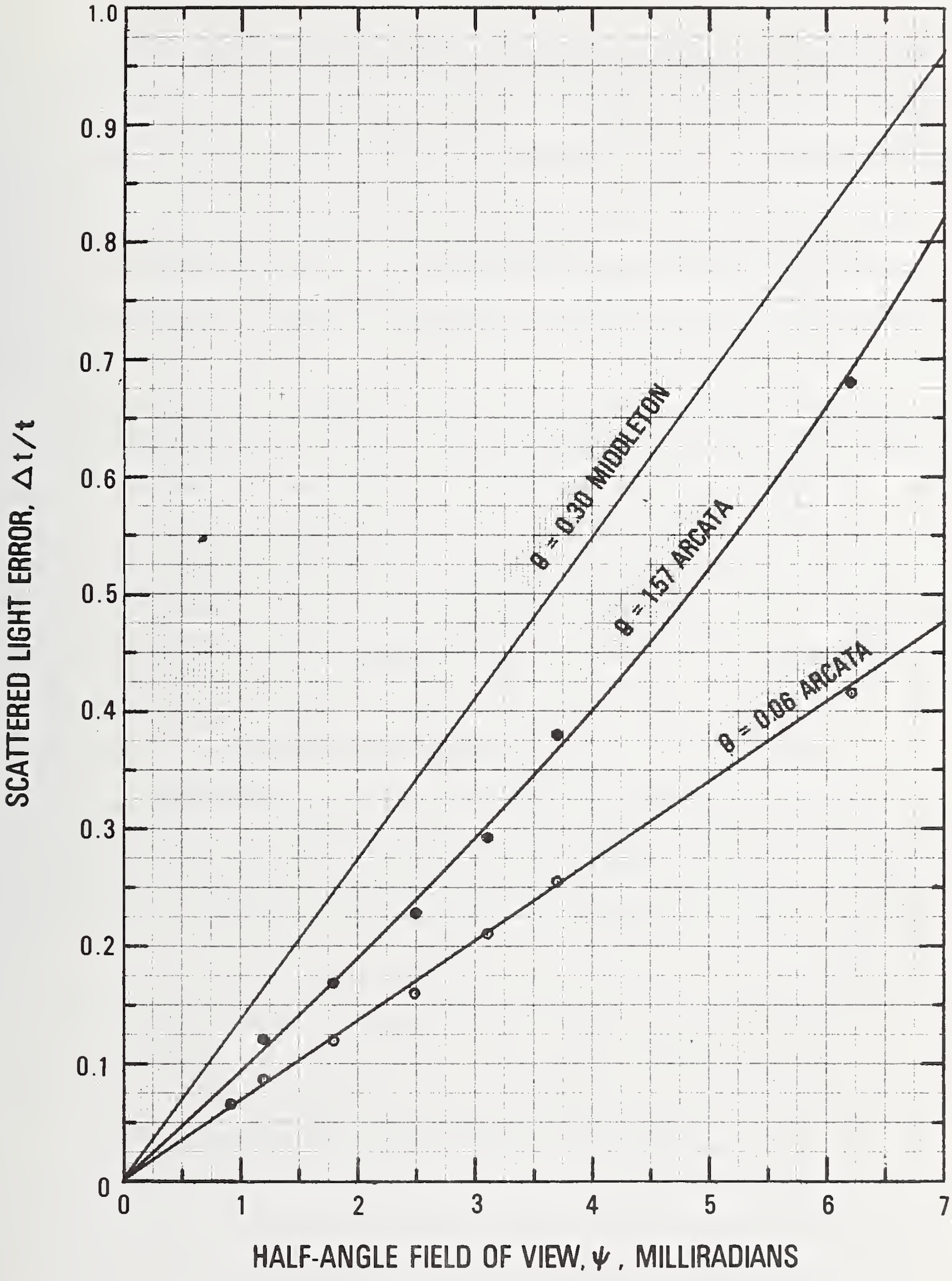


Figure 5.11 A comparison of scattered light errors obtained by Middleton with those from Arcata for different source (θ) and receiver (ψ) half-angle beam spreads. θ in radians. $t_b = 0.03$.

measurements of background luminance.

b) NBS obtained a higher number of data points.

Stewart and Curcio carried out measurements of scattered and directly transmitted light at distances of 2 miles along the shore of Chesapeake Bay and 9 miles across the open Bay [116]. Half-angle fields of view for the shorter distance were varied between 43.6 and 218 milliradians. The half-angle field of view at the larger distance was fixed at 0.118 radian. They investigated scattering at various regions of the visible spectrum by mounting Wratten filters in front of their detector. Data over the 2-mile range showed a gradual increase in $\Delta t/t$ toward the shorter wavelengths and a sharp increase at 360 nm over the 9 mile range. However, the baseline distances and receiver fields of view are so much greater than those of the NBS transmissometer that no conclusions can be drawn relative to transmissometer performance. Additionally, their measurements were carried out at transmittances ranging from 30 to 85% which are much higher than those found in fog.

The experiments at Arcata showed that errors due to scattered light are not as large as had been predicted. They are not significant in present-day operations of the NBS transmissometer which do not include RVR conditions below about 600 feet. Extensive baffling to reduce scattered light errors is unnecessary for today's operations.

Although the scattered light error is not significant for the fog densities under which the tests were conducted, it will become significant at very high fog densities. The effect of the scattered-light error on the indicated visual range is independent of the transmissometer baseline for a given *transmissivity* although the scattered light error for a short baseline instrument will be lower because of the higher transmittance over the short baseline [108].

5.1.4 Background Illuminance Errors

Some light from the background of the transmissometer projector will enter the receiver and impinge upon the photoreceiver. In addition, during periods of low transmittance, aerosols in the light path between the projector and the receiver will scatter light from the surround into the receiver. Usually the effect of this light on the accuracy of the transmission measurement is of concern only in daylight.

The effects of background illuminance are greatest in instruments which use unmodulated light because then the output of the receiver is proportional to the sum of the illuminance from the projector and the background illuminance. (This problem in the NBS transmissometer is analyzed in detail in Section 6.3.2.1). The effects of background illuminance can be reduced by:

a. Restricting the field of view of the receiver to the smallest angle compatible with the size of the projector and maintenance of receiver alignment.

b. Orienting the transmissometer receiver in a northerly direction (in the northern hemisphere).

c. Using baffles and blackened surfaces in the receiver to reduce interreflections. (See figure 6.4).

d. Using a projector of high intensity.

Other methods of reducing the effects of background illuminance are the use of a modulated light beam and a tuned receiver, e.g., use of a projector which emits short flashes of very high intensity and a receiver designed to respond to these flashes. It should be noted that the use of these methods does not eliminate the need to restrict the field of view of the receiver since a restricted field of view is required to reduce the scattered light error.

5.2 SCATTERING COEFFICIENT METERS

In many meteorological situations, almost all of the extinction of a beam of light is due to scattering. When this is true, as with "clean" fogs, absorption may be neglected completely and the scattering coefficient β may be substituted for the extinction coefficient σ. This being the case, equation (2.13) may be written as follows:

$$T = e^{-\beta}, \tag{5.31}$$

where β is the (total) scattering coefficient. Thus, under these conditions visual range may be determined by measuring the scattering (and hence the extinction coefficient) and applying these measurements to Koschmeider's and Allard's laws, which may be expressed as:

$$\varepsilon = e^{-\sigma V}, \tag{4.07}$$

and

$$E_t = I\ e^{-\sigma V}/V^2. \tag{4.22}$$

Since the concept of obtaining visual range through measurements of scattering assumes that extinction of a light beam is due solely to scattering, the use of such instruments should be avoided in industrial regions or regions where significant absorption is probable because of the presence of environmental pollution. Scattering coefficient meters are more appropriate for use at sea, for example on aircraft carriers, because a) absorption is usually negligible over the open sea, b) the uniformity of the atmosphere minimizes the consequences of the small sample, and c) the compact design permits use of an instrument of this type under conditions where a transmissometer with the required baseline could not be installed.

Extinction coefficient meters may be grouped into three general types: a) backscatter meters, b) sidescatter meters, and c) forward scatter meters. These three groups will be discussed separately in the Sections following.

5.2.1 Backscatter Meters

A backscatter meter consists of a light source and receiver located nearly adjacent to one another. Both are oriented in the same direction and slightly inclined towards each other, which allows the optical axes to intersect at a known distance. Typically, the light source emits either modulated light or short pulses of light, a portion of which is scattered back toward the receiver. The strength of this backscattered signal is then correlated to atmospheric transmittance through a knowledge of the instrument's calibration. A simplified arrangement is shown in figure 5.12. The darkened portion of the diagram represents the volume of air that is capable of scattering light rays back into the receiver.

Since the basic components of a backscatter meter are the same as those of a transmissometer, backscatter meters are sometimes erroneously referred to as single-ended transmissometers.

The ultimate usefulness of backscatter measurements depends on the existence of some relationship between backscattered light and atmospheric transmittance for actual atmospheric conditions. As previously mentioned, the attenuation of light by the atmosphere is due to both scattering and absorption, with scattering predominating in the visible spectrum. The volume scattering coefficient is defined as the total amount of light scattered by unit volume of air for unit volume of incident illumination. Backscattered light is only a fraction of the total amount of light scattered. The relation between light scattered in a given direction, as is the case with the backscatter meter, and the total scattering coefficient is not constant but depends upon the particle size distribution of the scattering medium. An excellent analysis of this problem is given by Twomey and Howell [119] who compared white and monochromatic light (700 nm) as sources for measurement of backscatter in determining visibility. They computed the ratio of reflectivity (backscatter signal) to extinction coefficient for the four possible separate combinations of monochromatic and heterochromatic sources incident upon scattering media both homogeneous and heterogeneous in drop-size. These computations showed that increasing the wavelength band of the illuminating light reduces the excursions in this ratio caused by the sharp maxima and minima found in the Mie scattering coefficient and intensity function for a single particle size and wavelength. Thus the use of a broad-band source, such as a xenon lamp, is preferable to the use of a monochromatic source, such as a laser.

There have been several field studies of the relation between atmospheric transmissivity and the response of backscatter meters in a real atmosphere. An early study was conducted by Born and Franz [14] who, in the late 1920's, made simultaneous measurements of atmospheric transmittance and scattered light.

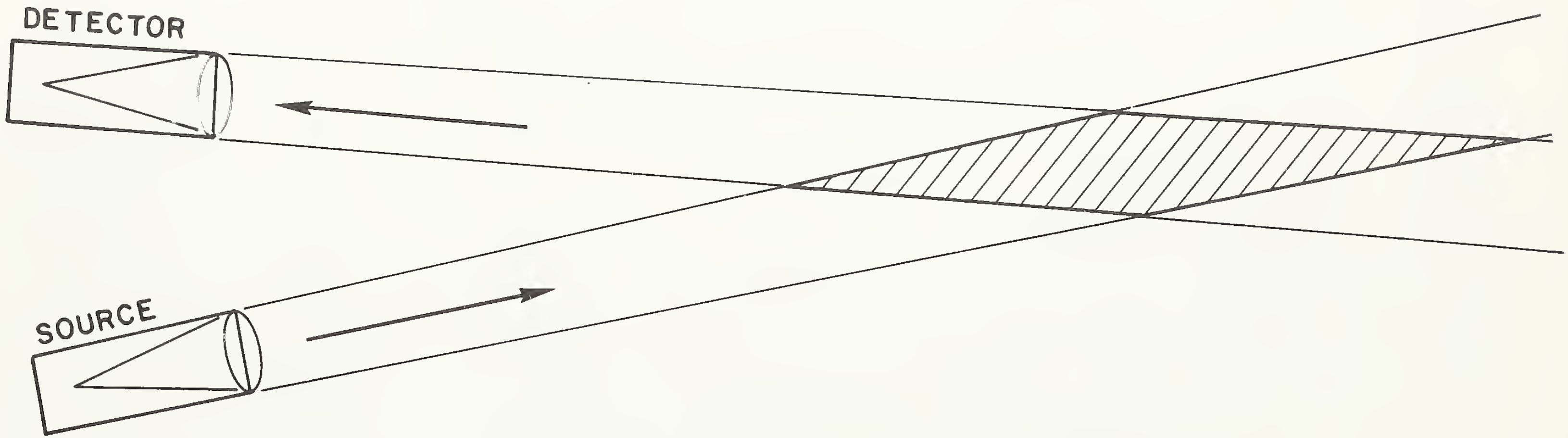


Figure 5.12 Simplified schematic arrangement of a backscatter meter. In practice, the two paths shown would usually be more nearly parallel.

The study by Curcio and Knestrick [23, 24] provided a practical basis upon which backscatter visibility instruments depend for useful measurements. Their experiments provided data from which the relationship

$$MR = k\ S^{-1.5} \tag{5.32}$$

was derived, where

MR is the meteorological range (obtained from transmittance measurements assuming ε is 0.02),

k is a constant, and

S is the backscatter signal.

Measurements were made correlating backscatter measurements with transmittance measurements for a variety of conditions where the meteorological range varied from less than 0.10 mile to more than 40 miles in atmospheres which were free of industrial pollution. Their results are summarized in figures 5.13a and 5.13b. Curcio and Knestrick concluded that the point spread about the curves indicates that visibility can be determined from the backscattered signal with an accuracy of 20% for all visibilitities in the ranges studied. This favorable result can be explained theoretically only on the assumption that the sizes of the scattering particles are so irregularly distributed in the atmosphere that their total effect is to produce backscattering almost independent of the type of fog. First order theory indicates that, for a given particle size distribution, the exponent of S should be -1. Hence, the value of -1.5 may be considered as an empirical correction for a quasi systematic change in particle size distribution with atmospheric clarity.

However, it should be noted that in their analysis the data were normalized to force a match at a visibility of 1.5 miles of data taken at Arcata, in meteorological ranges of 0.1 to 1.5 miles, and of data in the range 1 to 40 miles, taken at the Naval Research Laboratory. This normalizing would conceal any systematic differences in the two sets of data. Close visual examination of the data in figure 5.13b indicates an exponent in (5.32) somewhat less than

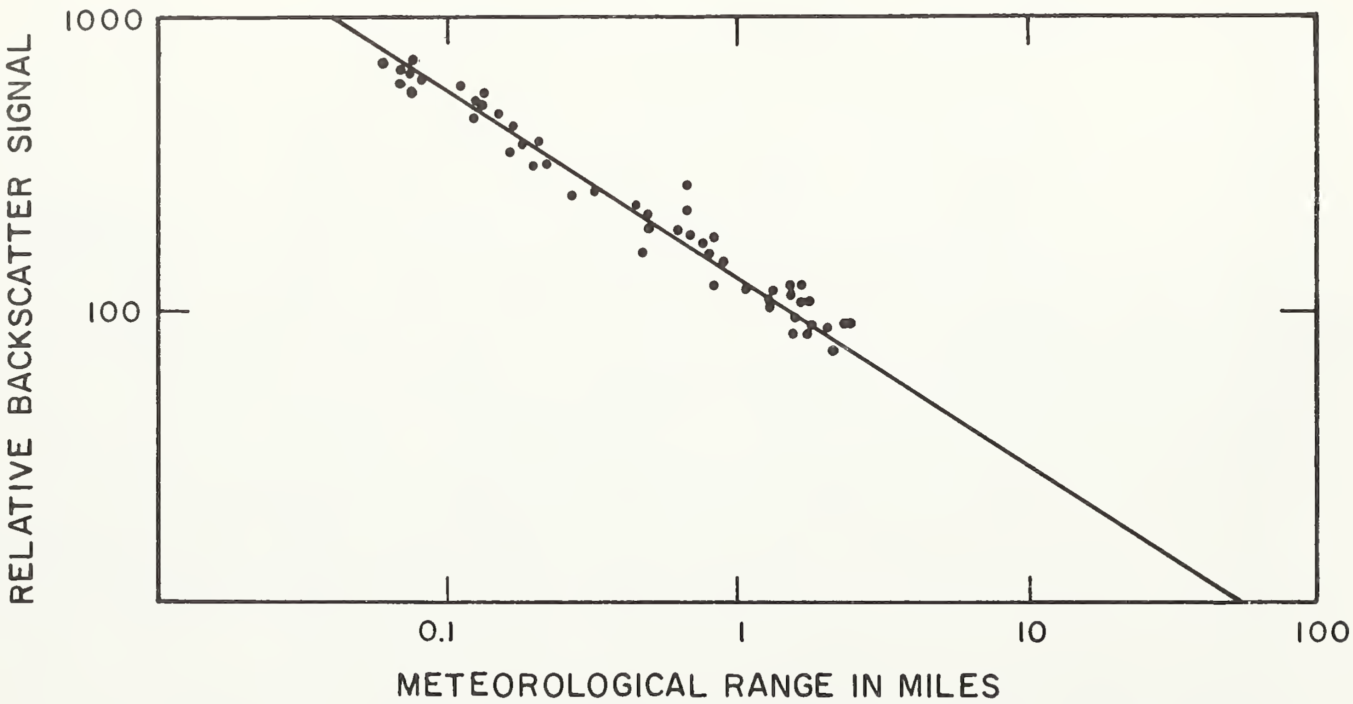


Figure 5.13a Relative backscatter signal in fog as a function of meteorological range obtained by Curcio and Knestrick [23].

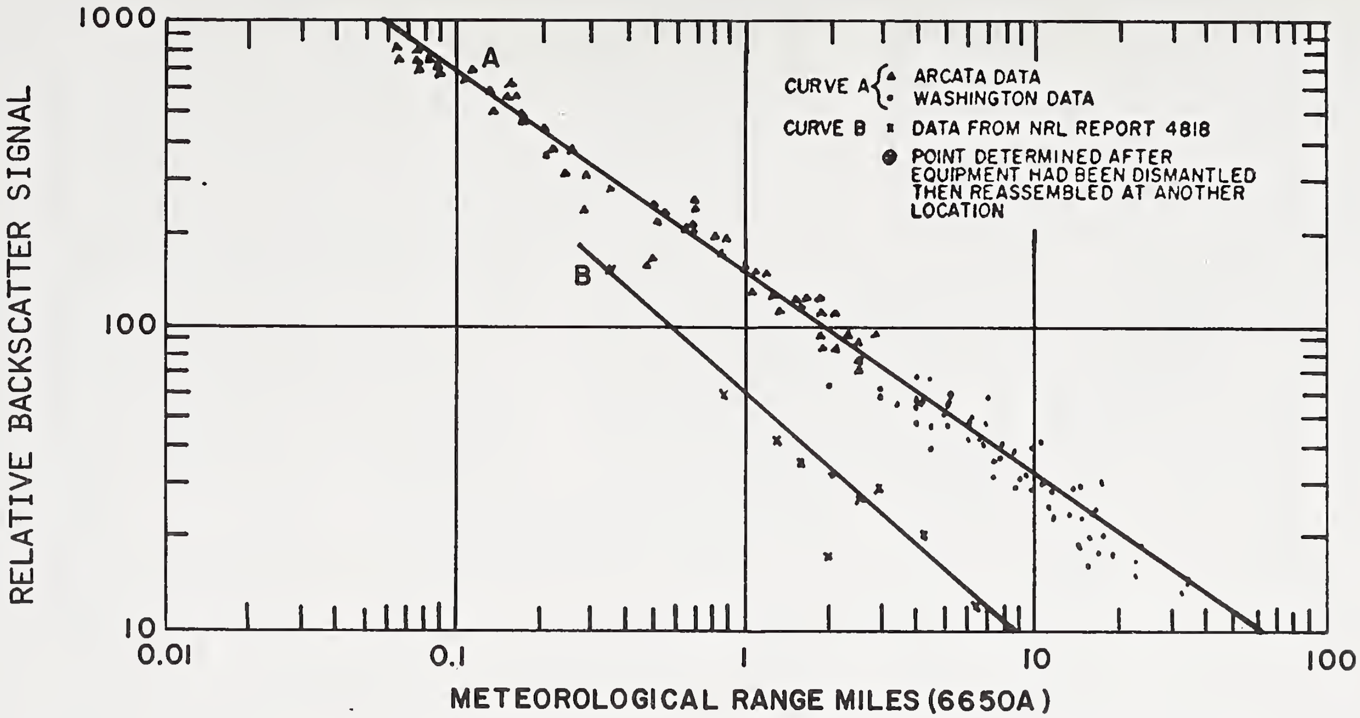


Figure 5.13b Composite of Arcata and NRL data normalized at 1.5 miles to give straight line curve [23].

-1.5 (about -1.7) for meteorological ranges above 1.5 miles and somewhat greater (about -1.1) for the lower meteorological ranges. Nevertheless linearity of the log-log curve over the wide range of 0.10 to 40 miles is surprisingly good.

Vogt conducted tests in Germany which demonstrated that backscatter devices indicate visibility equally well as other types of visibility meters with an accuracy of about ±20%, provided that no completely abnormal distribution of aerosol particles occurs [121]. (Note that Vogt's estimate of accuracy coincides with that reported by Curcio and Knestrick.) Vogt used a commercially available backscatter device and compared its measurements with estimates of visibility carried out by experienced observers. When the visibility was estimated simultaneously by eight observers in eight different directions, the average of these values seldom deviated from backscatter recorder determinations by more than ±25% and the standard deviation was only 12%.

It should be noted, however, that a requirement for different calibration curves for snow conditions and for rain is evident in a recent study of the Sterling Research and Evaluation Center [104]. Sweden has found it necessary to use three sets of calibration curves--fog, rain, and snow--in their application of backscatter meters to airfield operations [113].

Twomey and Howell [119] compared their computations of the ratio of backscatter to extinction coefficient for one of their combinations (white light and heteorogeneous scatters) with field measurements made by Curcio, et al. Figure 5.14 shows the computed relative backscattered signal R plotted against meteorological range. Included in this figure are points (triangles) from a similar curve by Curcio. When this is compared to figure 5.15, which represents similar conditions but with monochromatic illumination, it is apparent that the correlation between backscatter and meteorological range is very much lower when the smoothing effect of the spread in wavelength is absent. Based on these findings, it is concluded that narrow band light sources are inferior to heterochromatic sources.

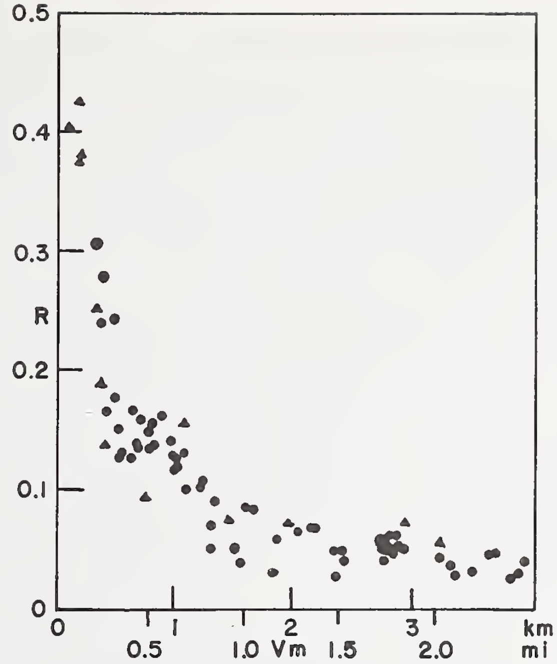


Figure 5.14 Backscatter signal as a function of meteorological range for white light ($0.4\mu \leq \lambda \leq 0.7\mu$). Key: 0, result of simulation study; Δ data from Curcio, Krestrick, and Cosden. From Twoomey and Howell [119].

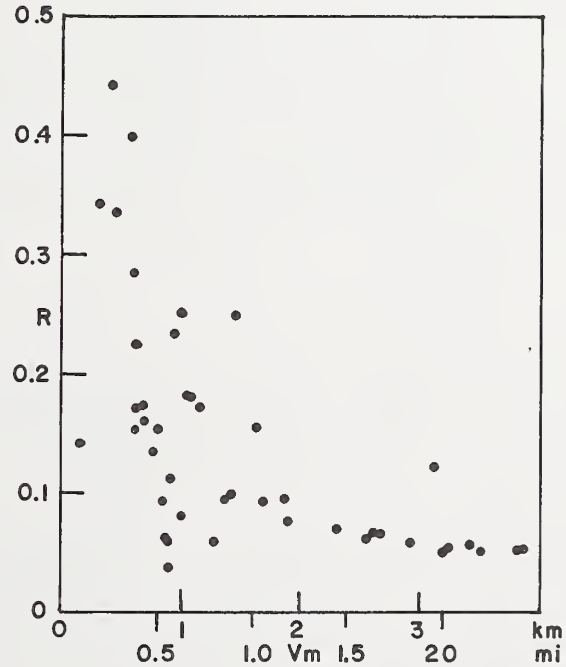


Figure 5.15 Backscatter signal as a function of meteorological range for monochromatic light ($\lambda = 0.7\mu$). From Twoomey and Howell [119].

The work reported above may not apply to all real particle size distributions. Hence, when backscatter instruments are calibrated by means of parallel transmittance measurements, calibrations should be performed in a region where the mean particle size distribution is similar to that in the intended area of operation.

Frequently the statement is made that inclining a backscatter meter of the integrating type shown in figure 5.12 along a runway glide path will yield a measure of the slant visibility. This concept is very much in error. In fog scattering, nearly all the response of a backscatter meter is produced by scattering very near the instrument. Curcio and Knestrick reported 90% of the backscattered signal from the first 100 feet in fog conditions [23]. In instruments which have been analyzed at NBS, more than 80% of the response comes from scattering within the two hundred feet nearest the instrument when the transmissivity is such that the day visibility is less than one mile. If the instrument was inclined at a glide slope angle of 3° the *outer end* of this 200 foot region would be only 10 feet above the instrument. Compare this with a transmissometer baseline height of 15 feet.

It should be noted that Lidar or gated instruments, which measure the backscattered signal as a function of distance from the instrument, sample at a considerably greater distance than do integrating type instruments. However, these instruments must be inclined at angles considerably greater than the glide slope to obtain adequate signals up to the maximum desired height.

5.2.2 Forward Scatter Meters

In forward scatter meters the receiver accepts light from a source which has been scattered in a near-forward direction as illustrated in figure 5.16. In his classic study, Waldram [122] found that the scattering coefficient in the direction of an angle of about 150° between the axis of the beam and the axis of the receiver was nearly independent of the particle size distribution of the atmosphere. Hence, forward scatter meters are expected to be less sensitive to particle size distribution than are backscatter meters. As stated by Waldram in discussing his polar scattering coefficient curves; "A consideration of the curves

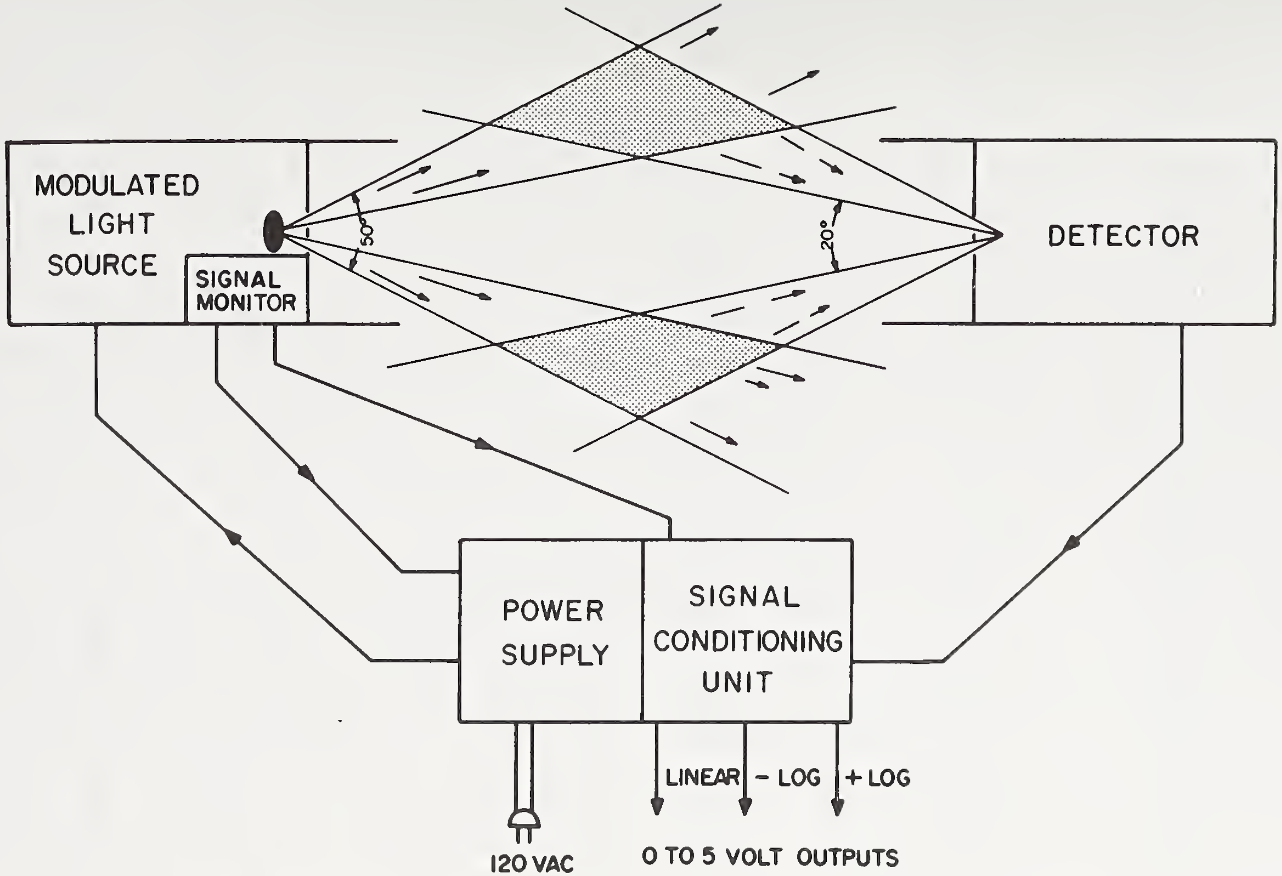


Figure 5.16 Schematic diagram of the Air Force Forward Scatter Meter. [100]

shows that in most cases the polar scatter index, for a given scattering coefficient, is fairly constant in the region of 150 deg., but is very much more variable at the tail of the curve representing back scatter. This is simply because in most curves the forward scatter is much greater; consequently the flux in a (say) 5-deg. zone is a maximum near 150 deg. The total flux represented by the polar distribution, and consequently the scattering coefficient, is therefore usually governed by the polar scatter index in this region. There are however, some interesting consequences. It follows that back scatter for a given scattering coefficient, may vary widely...."

Waldram then reports that experiments which depended upon backscatter as a measure of the volume scattering coefficient were unsuccessful, but that later experiments based upon forward scatter were more successful.

The current state-of-the-art is represented by the forward scatter meter developed for the Air Force [42].* (Shown in figure 5.16). The light from a halogen-cycle projector lamp is mechanically chopped at 290 Hz before entering an optical system that projects a cone of light, with an inner cone masked out. A photodiode detector is located 120 cm from the projector and receives light from a similar cone-shaped volume. The intersection of the projection and viewing cones forms a sampling volume of 0.05 m^3; projected light scattered by particulates within this volume at angles between 20 and 50 degrees is accepted by the detector. Synchronous modulation is used in detecting the scattered light. The detected energy is proportional to the extinction coefficient σ assuming that (a) forward scattering is proportional to total volume scattering, and (b) atmospheric absorption is negligible relative to attenuation by scattering.

This instrument has been thoroughly evaluated through comparisons with both transmissometers and human observers. The feasibility models were tested primarily at the U.S. Naval Radio Station, Cutler, Maine in August, 1970 [100]. The prototype and production models

*Manufactured by EG & G.

were tested primarily at three military installations in the fall of 1972 by comparison with transmissometers. Comparisons with visual determinations was also conducted at one of the sites.

Results obtained at these three sites are shown in figure 5.17 and table 5.6. Note that effects of inhomogeneities in fog were minimized by time-averaging the data over five-minute periods and data with RMS variations greater than ±15 percent were excluded from the sample.

Note also that the relation between meteorological range and the forward scatter signal of this instrument is of the form

$$MR = kS^{-1},$$

whereas Curcio and Knestrick (Section 5.2.1) obtained an exponent of -1.5 in their study of back scatter. In addition, one straight line fits the data of figure 5.17 very well. These considerations demonstrate that forward scatter meters are less affected by changes in particle size distribution than are back scatter meters.

Table 5.6
Correlation of Extinction Coefficients from Forward Scatter Visibility Meter Against Transmissometer (based on logarithms)*

Station Number	Station Location	Number of Comparisons	Correlation Coefficient	RMS Difference (%)	Slope
07	N. Ipswich	200	0.93	± 20	0.92
10	Boston Hill	435	0.99	± 16	0.99
23	Nike Site	84	0.96	± 22	1.00
All combined		729	0.98	± 19	0.98

*From Muench, Moroz, and Jacobs [100].

5.2.3 Side-Scatter Meters

The design of side-scatter meters is based upon the work of Beuttell and Brewer [8]. The principles of the design of instruments of this type are illustrated by figure 5.18. The light source is a perfect diffuser and the axis of the photometer is parallel to the plane of the source. Under these circumstances the response of the photometer is proportional to the total scattering coefficient, β,

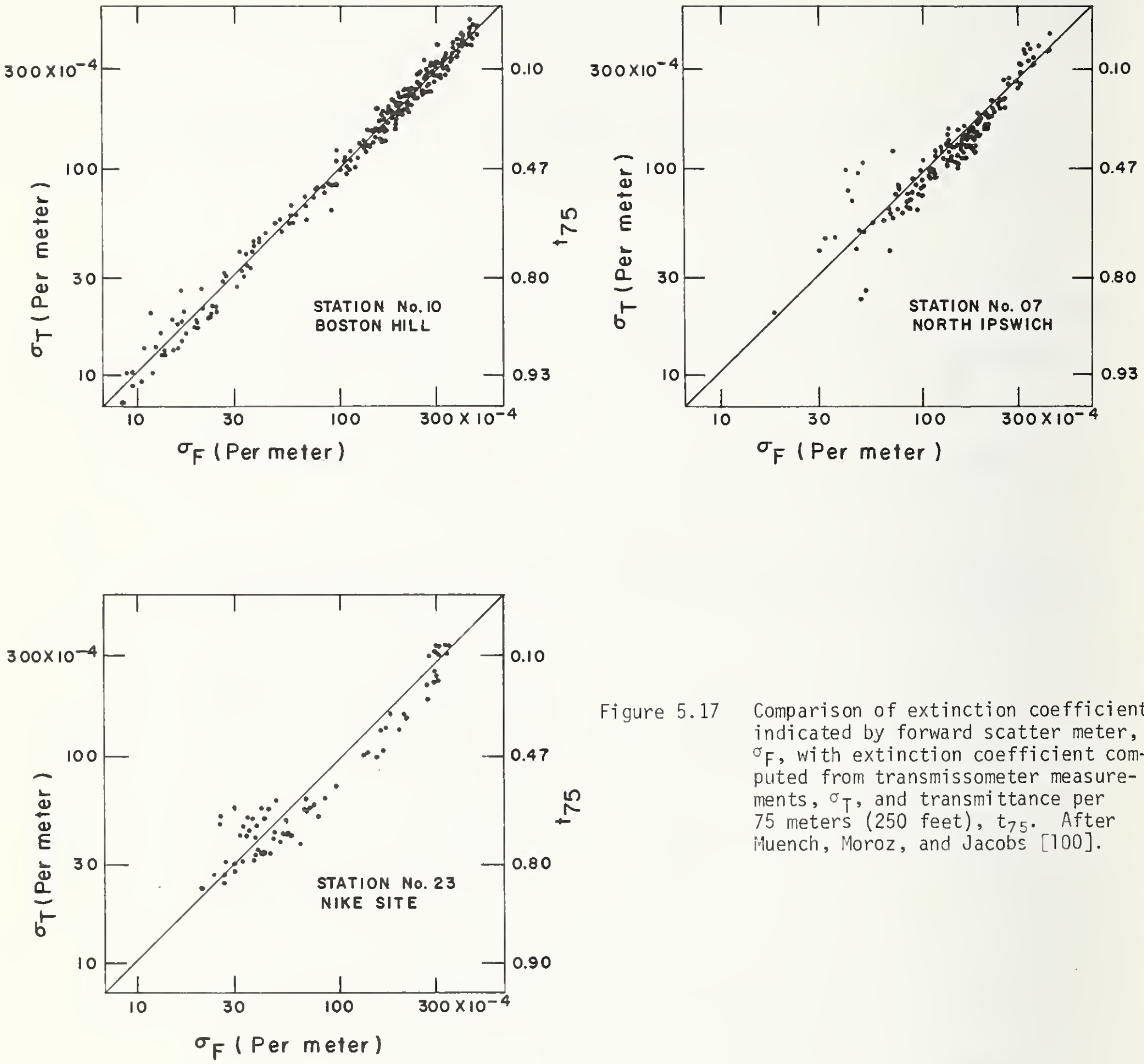


Figure 5.17 Comparison of extinction coefficient indicated by forward scatter meter, σ_F, with extinction coefficient computed from transmissometer measurements, σ_T, and transmittance per 75 meters (250 feet), t_{75}. After Muench, Moroz, and Jacobs [100].

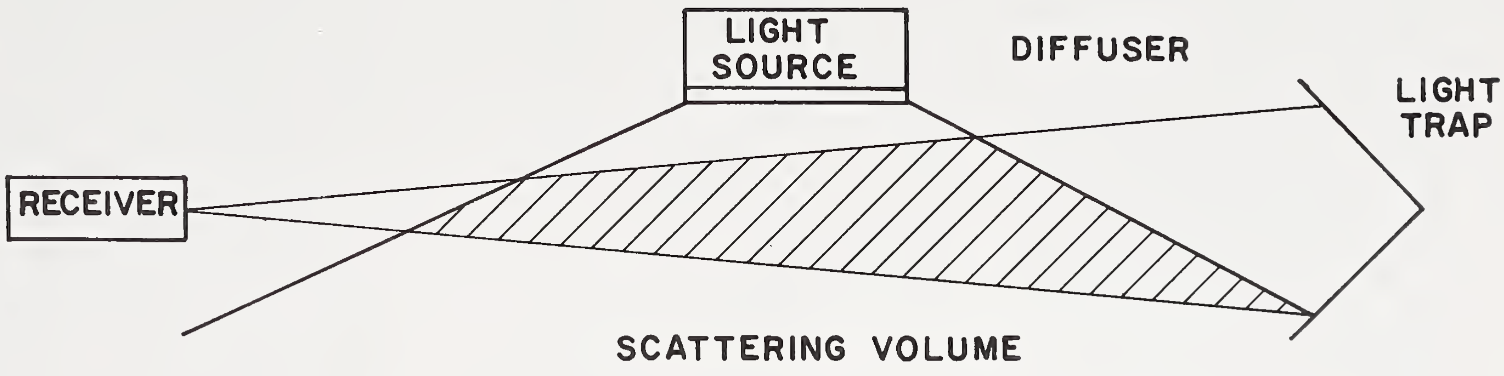


Figure 5.18 Schematic diagram of a sidescatter visibility meter.

and hence, is independent of the particle size distribution of the aerosols. Ideally, the rays limiting the scattering volume should form an angle of 180°. However, this can only be approximated in practice.

Instruments of this type have been used in the study of air pollution [1], on board ships at sea [112] and an instrument has been designed for airport and fog detector use; but apparently no instruments of this type have been adopted for operational use.

5.2.4 Error Analysis of Scattering-Coefficient Meters

5.2.4.1 Relative error in the visual range of objects

The following error analysis applies to all types of scattering-coefficient meters, backscatter-meters, side-scattering meters, and forward-scatter meters.

From Koschmieder's law,

$$\varepsilon = C_o e^{-\sigma V}, \tag{4.10a}$$

and

$$\ln C_o - \ln \varepsilon = \sigma V. \tag{4.11a}$$

Differentiating,

$$\sigma dV = -V\, d\sigma.$$

Then for small finite errors,

$$\sigma \Delta V = -V \Delta\sigma,$$

and

$$\Delta V/V = -\Delta\sigma/\sigma. \tag{5.33}$$

If atmospheric absorption is negligible, the extinction coefficient, σ, and the volume scattering coefficient, β, are equal. If the particle size distribution of the aerosols does not significantly affect the response of the scattering meter, the instrument measures σ. Hence under these conditions, the relative error in the visual range of objects obtained from scattering type meters measurements is equal to the relative error in the meter indication.

The negative sign indicates that a negative error in σ produces a positive error in V, the visual range. Note that the relative error in the indicated visual range is independent of the visual range itself and of the inherent contrast of the object viewed.

Note that equation (5.33) does not take into account the effects of a non-uniform atmosphere, absorption, and the effects of particle size distribution.

5.2.4.2 Relative error in the visual range of lights

The analysis of the relative error in the visual range of lights as a function of the relative error for scattering coefficient meters is very similar to the corresponding analysis for transmissometers.

From Allard's law

$$E_t = Ie^{-\sigma V}/V^2. \tag{4.22}$$

Taking natural logarithms and transposing,

$$-\sigma V = [2 \ln V - \ln I/E_t]. \tag{4.23}$$

Differentiating, holding I and E_t constant, and rearranging terms,

$$\sigma dV + V\, d\sigma = -2\, dV/V,$$

or

$$dV/V = -d\sigma/(\sigma + 2/V), \tag{5.34}$$

or, for small finite errors

$$\Delta V/V = -\Delta\sigma/(\sigma + 2/V). \tag{5.35}$$

As with the error analysis of transmissometers (Section 5.1.2.2), an explicit expression for $\Delta V/V$ cannot be obtained. However, the term $(\sigma + 2/V)$ is always greater than σ alone, since V is always positive. Therefore for lights

$$\Delta V/V < (-\Delta\sigma/\sigma). \tag{5.36}$$

Thus for a given instrument error, $\Delta V/V$, the error in the indicated visual range of lights, is less than the error in the visual range of objects and (5.36) may be taken as the limiting equation.

5.2.4.3 100% calibration errors in scattering coefficient meters

The problems involved in the 100% calibration of scattering coefficient meters are quite different from those involved in the 100% calibration of transmissometers:

a. Calibration cannot be accomplished by separate measurements of the output of the source and the sensitivity of the receptor since the scattering volume common to the light beam and the receiver field of view is not known with sufficient accuracy. (However, see 5.2.4.4b).

b. Satisfactory calibration cannot be obtained from observations of the prevailing meterological visibility for, as shown below, the error in indicated visibility which is produced by a calibration error is the same for all visibilities, and does not decrease with decreasing visibility as is the case for a transmissometer, as shown by the following.

Let

V_o be the "true" prevailing object visibility during calibration and

c_o be the corresponding extinction* coefficient; computed from Koschmieder's Law, (4.07), and

V_e be the estimated object visibility at the time of calibration, and

σ_e be the corresponding extinction coefficient.

Then, from (4.07),

$$\sigma_o/\sigma_e = V_e/V_o. \tag{5.37}$$

To determine the effect of this error in 100% calibration, let

σ' be the extinction coefficient indicated by the instrument during operational use and

σ be the true extinction coefficient.

---

* The term "extinction" is used in place of "scattering" in this discussion as the principles are applicable to extinction as well as scattering meters.

Then,

$$\sigma = \sigma' \, \sigma_o/\sigma_e,$$

or

$$\sigma = \sigma' \, V_e/V_o. \tag{5.38}$$

If V' is the object visibility indicated by the instrument, and V is the "true" object visibility, then since

$$\sigma' \, V' = \sigma V,$$

from (5.38)

$$V'/V = V_e/V_o. \tag{5.39}$$

Thus, if during 100% calibration by visual estimates, the visibility is estimated as 20 miles when the atmosphere at the instrument site is representative of a 10 mile visibility, a visibility of 500 feet will be reported as a visibility of 1000 feet.

Note that the above equations are independent of the contrast threshold, ε. This means that the accuracy of the indication is independent of the value used for ε if the same value is used for both calibration and service. (Conversely, comparisons of visual range observations with measurements of the extinction coefficient by an instrument calibrated by visual estimates cannot be used to determine the value of ε. Apparently, this factor has been frequently overlooked.)

c. Once a stable reference scattering coefficient meter is calibrated, it can, of course, be used to calibrate similar instruments by comparison in the laboratory or in the field.

d. It also is possible to calibrate scattering coefficient meters using calibrated standard samples of a scattering material, such as Teflon, mounted so that they may be repositioned accurately. These calibration samples would be calibrated on the reference instrument.

5.2.4.4 Methods of calibrating scattering coefficient meters

It is apparent that the primary problem in the 100% calibration of scattering coefficient meters is the 100% calibration of the first, or reference, instrument. At present there are two methods which are feasible:

a. Direct comparison with a transmissometer. Comparisons should be made when the transmittance is low enough so that the relative uncertainties in the visibility indicated by the two instruments are roughly equal. On this basis the optimum transmittance is 0.37 as shown in Section 5.4. However, a transmittance this low may cause difficulties because of non-uniformities in the fog as the scattering coefficient meter would sample only a small part of the transmissometer path.

b. If the instrument is sufficiently sensitive, it may be calibrated by placing it in a chamber which contains an atmosphere (gas) whose scattering coefficient can be computed from theory [1]. One such gas is clean dry carbon dioxide.

5.3 MISCELLANEOUS TRANSMITTANCE METERS

In addition to the two general classes of meters described above there are some transmittance meters under development which can be classed as hybrids. These instruments are single-ended devices, intended for use as slant visibility meters, in which light scattered from a small section of the light beam projected by the light source of the instrument is viewed by the receiver.

One such instrument uses Raman scattering from the nitrogen in the air induced by a pulsed ultra-violet (nitrogen) laser. The intensity of the Raman scattering from the scattering volume can be computed from the characteristics of the laser source and the characteristics of Raman scattering [90a].

Another type is the "Lidar" type described by Horman [47], Collis [22] and Brown [18]. In this type of instrument the source is a pulsed laser, the receiver looks out along the beam and is time-gated so that signals are accepted from scattering volumes at different distances. Transmittance is determined from the change in receiver output as a function of distance. These instruments may be used as slant visibility meters, and fall outside the scope of this report. See Section 5.2.1 for comments on the use of integrating type backscatter meters to indicate slant visibility.

A third type instrument which has been proposed for the determination of RVR is a photoelectric instrument which scans a row of runway lights and counts the number visible [17]. No reports of operational use of instruments of this type are available.

5.4 COMPARISON OF TRANSMISSOMETER AND SCATTERING COEFFICIENT METER ACCURACY

It is useful to compare the accuracy of visibilities indicated by scattering coefficient meters with the accuracy of visibilities indicated by transmissometers.

For scattering coefficient meters

$$\Delta V/V = -\Delta\sigma/\sigma, \qquad (5.33)$$

and for transmissometers

$$\Delta V/V - -(V/b \ln \varepsilon)\ \Delta t_b/t_b. \qquad (5.09b)$$

If the instrumental errors are equal, the errors in the visibilities indicated by the two types of instruments will be equal when

$$V = b \ln \varepsilon. \qquad (5.40)$$

If a value of 0.05 is assumed for ε,

$$V = 3b. \qquad (5.41)$$

When the visibility is three times the baseline, the transmittance over the baseline, b, is given by

$$t_b = \varepsilon^{b/V}.$$

Since b/V is 0.333,

$$t_b = 0.37.$$

Thus, by day, if the visibility is less than three times the length of the transmissometer baseline (the transmittance is less than 0.37), the instrumental errors of the transmissometer have less effect on the determination of visibility than do the instrumental errors of scattering coefficient meters and for higher transmittances the instrumental errors of scattering coefficient meters have less effect.

5.5 EFFECTS OF ERRORS IN ASSUMED THRESHOLD ON THE ACCURACY OF VISIBILITY METERS

The effects of assuming a threshold inappropriate to the circumstances on the relation of the indicated visual range to what is seen may be analyzed in a manner similar to that used in analyzing the effects of instrumental errors.

Let

- ε be the applicable contrast threshold,
- V be the corresponding object visibility,
- ε' be the inappropriate contrast threshold, and
- V' be the indicated visibility obtained using this threshold.

Since

$$\varepsilon = t_b^{V/b}, \qquad (5.01)$$

and

$$\varepsilon' = t_b^{V'/b},$$

then

$$V'/V = \ln \varepsilon'/\ln \varepsilon. \qquad (5.42)$$

If a value of 0.02 is chosen for ε' and a value of 0.055 for ε,

$$V'/V = V_{.02}/V_{.055} = MR/V_{.055} = 1.35 \qquad (5.43)$$

Similarly, if ε' is 0.05 and ε is 0.055

$$V_{.05}/V_{.055} = 1.03. \qquad (5.44)$$

Also,

$$MR/MOR = 1.30. \tag{5.45}$$

From this it is apparent that the indicated visual range of objects is not overly sensitive to the value used for the contrast threshold.

As before, when lights are involved, the analysis is more complex because of the effects of the inverse square law and because the effects are dependent upon the intensity of the light and the fog density transmissivity as well. Analysis, shows that, at night, if the illuminance threshold is changed by a factor $\underline{f}$, the percentage change is visual range of nearly all lights is less than it would be for an object by day if the contrast threshold were changed by the same factor. The change in the visual range of a light by day would be less than the change in the visual range of an object only if the intensity of the light is greater than about 20,000 candelas.

6. DEVELOPMENT AND APPLICATION OF THE NBS TRANSMISSOMETER

This chapter contains a brief description of the NBS transmissometer, an analysis of the theory of operation of the photometric system, a discussion of the sources of error in the photometric system, and an analysis of the effects of these errors on indicated visual range.

6.1 PRINCIPLES OF OPERATION

NOTE: A detailed theory of operation of the electronics of the NBS transmissometer is contained in the NBS-prepared Instruction Book for Transmissometer Set AN/GMQ-10 [103] and in the manuals which have followed it, and it will not be repeated here. However, a brief review will be given as an aid to understanding the analysis of the photometric system.

6.1.1 General

The transmissometer is essentially a remote-indicating photoelectric telephotometer. It consists of three major elements: (1) a projector operating at a fixed intensity; (2) a receiver consisting of a telescope of adjustable aperture and a photoelectric unit which provides an output signal in the form of pulses; and (3) an indicator with a dc output proportional to the pulse rate. An elementary block diagram of the first transmissometer (1941) is shown in figure 3.1. The complete circuit diagram of this instrument is shown in figure 6.1. As development proceeded, circuits were added or modified to permit transmission of the signal to a remote location, to calibrate the metering circuits, to improve stability, linearity, sensitivity, and to provide an RVR readout. However, the basic principles of operation have not been changed. Figures 3.9 and 3.10 show the present equipment. A brief description of this instrumentation is given below.

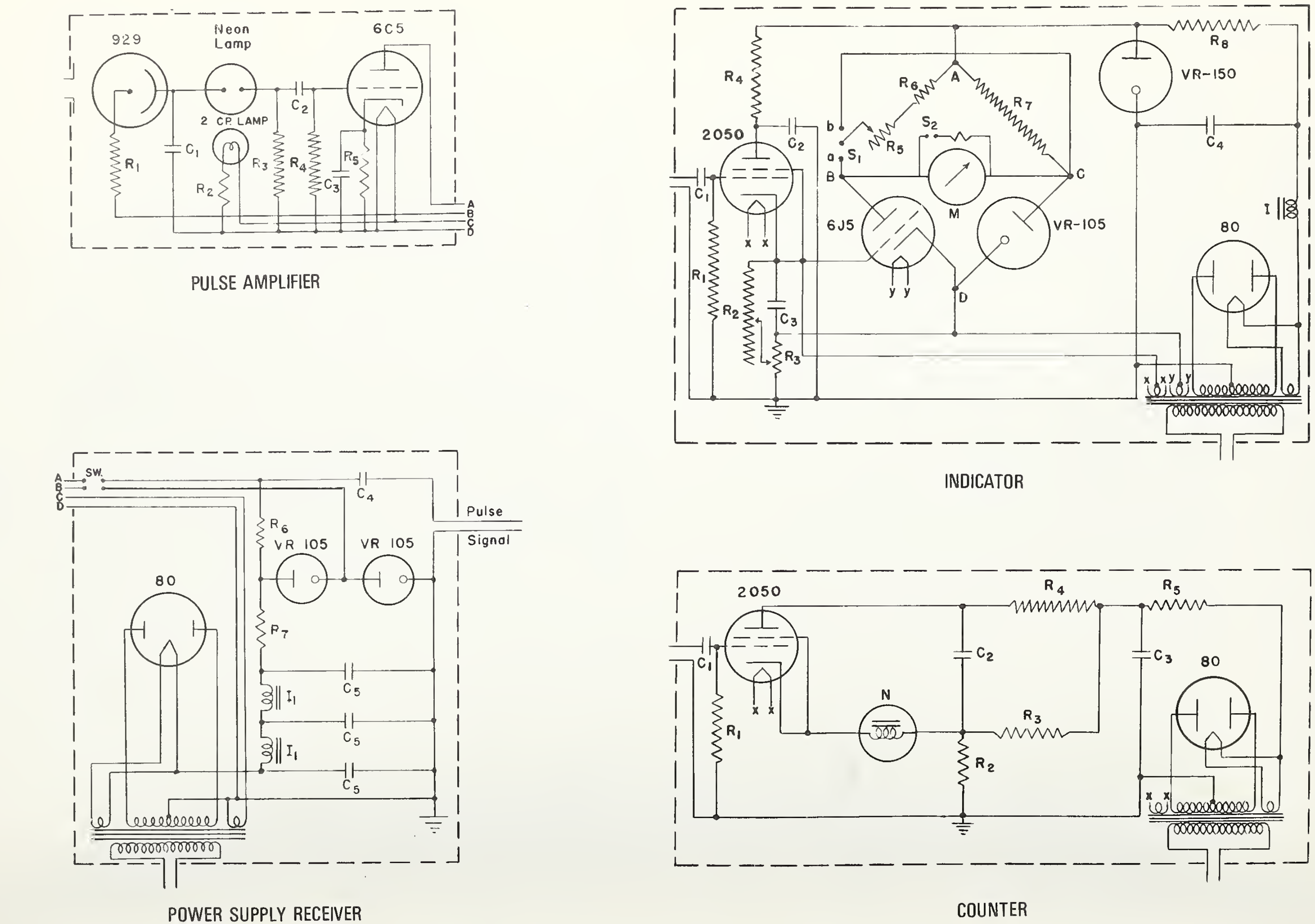


Figure 6.1 Circuit diagram of first NBS transmissometer.

6.1.2 Projector (See figure 6.2)

The projector consists of a reflector lamp mounted in a cast-aluminum housing, the alignment of which is adjustable.

The lamp is designed for use in the Transmissometer Set. It is a type PAR-64, sealed-reflector, lamp having a 6-volt, 120-watt, single-coil filament and is designed to operate for 3000 hours. The parabolic reflector of the lamp produces an essentially parallel beam with an intensity in the peak of the beam of approximately 140,000 candelas. The beam spread at 95% of peak intensity is 0.5° horizontal by 1° vertical and at 10% of peak intensity it is 5° horizontal by 10° vertical. A hemispherical shield within the lamp prevents direct (uncollimated) light from the filament leaving the lamp. A low-voltage, high-current filament is used to obtain the maximum peak intensity consistent with long life.

The housing supporting the lamp can be rotated through a horizontal angle of 6° and through vertical angles of plus or minus 3° from the horizontal plane and then locked in place. These adjustments permit alignment of the lamp to within 0.02°. In service the lamp is aligned so that the peak of the beam falls on the receiver. This minimizes the effects of small shifts in lamp alignment and the effects of background illumination.

A protective hood attached to the lamp housing extends beyond the lamp to protect its cover from dirt and debris.

The lamp may be turned off manually from the indicator or periodically from the hourly-check timer in the projector power supply to obtain measurements of the effect of background illumination upon the transmittance measurement.

Power for the lamp is regulated by a resonant-circuit voltage-regulating transformer which is frequency compensated when required. This tranformer maintains the lamp voltage constant to within 1% of supplied voltage when the input voltage to the projector is within the range 95 to 130 volts.

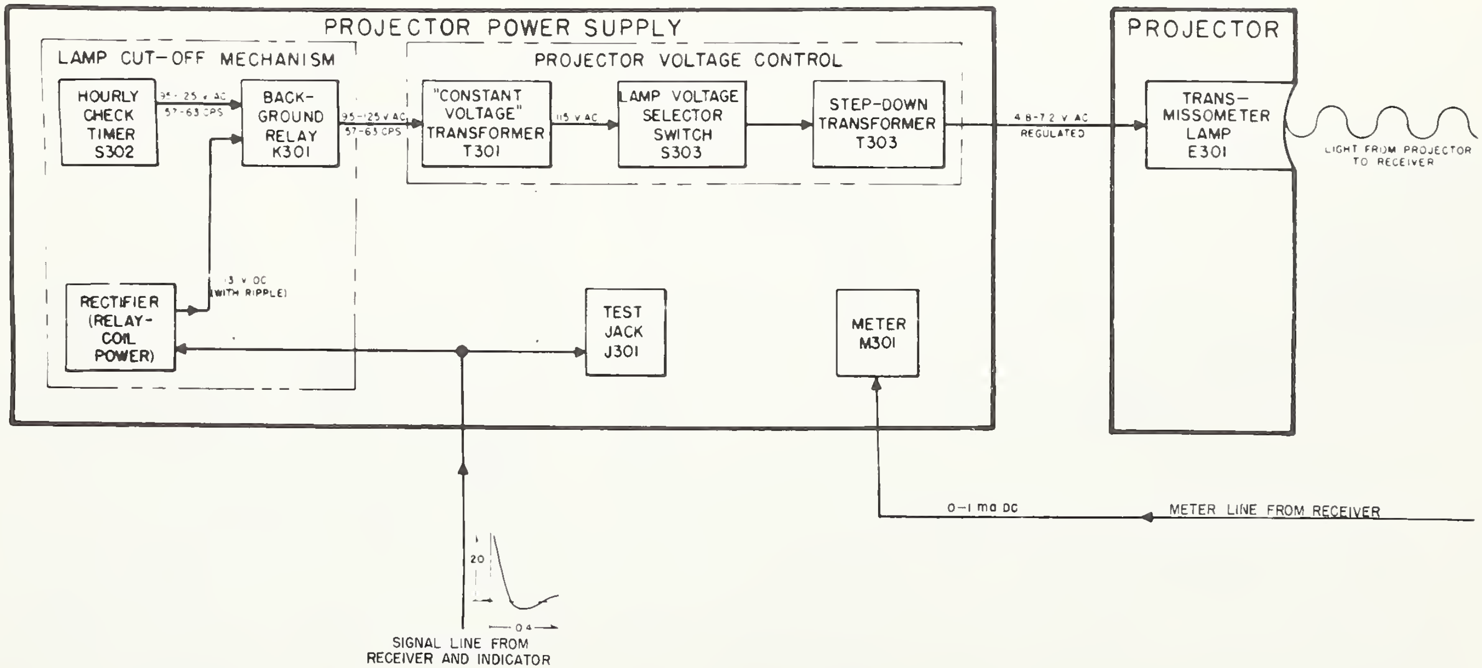


Figure 6.2 Block diagram of transmissometer projector and projector power supply [103].

A tapped stepdown transformer is used to reduce the output voltage of the voltage-regulating transformer from 115 volts to the low voltage required by the lamp. Five taps on this transformer permit a selection of the voltage applied to the projector lamp. These taps are in the primary of the step-down transformer so that the effects of contact resistance in the voltage-selector switch are minimized.

The resistances of the transformers and of the wiring in the projector power supply change slightly with the operating temperature of these parts. The projector lamp also requires some time to reach stability. These effects combine to produce a downward drift in the lamp intensity during the warmup period. The warmup period after the hourly cutoff is one to two minutes in length.

If an unseasoned lamp is placed in operation, the intensity will frequently increase for several days. The total increase in intensity may be as great as 15%. To eliminate this increase after the lamp has been placed in service, the lamp is seasoned at a current higher than that used in operation. Seasoning for eight hours at 22.5 amperes or 48 hours at 20 amperes will stabilize the lamp.

After the lamp has stabilized there is usually a slow drift upward in intensity until near the end of the useful life of the lamp. The lamp then becomes unstable with erratic changes in intensity. This instability is first evident as a small shift in transmissometer reading after the lamp has been turned off for a background check. The instability then increases within a few days until the transmissometer reading varies erratically over a range of about 10 percent of reading.

6.1.3 Receiver and Receiver Amplifier-Power Supply (See figure 6.3)

6.1.3.1 Optical System

The receiver is composed of a telescope which collects light from the projector and directs it onto a photoelectric receiver (the pulse amplifier) which produces a pulse signal with a pulse rate proportional

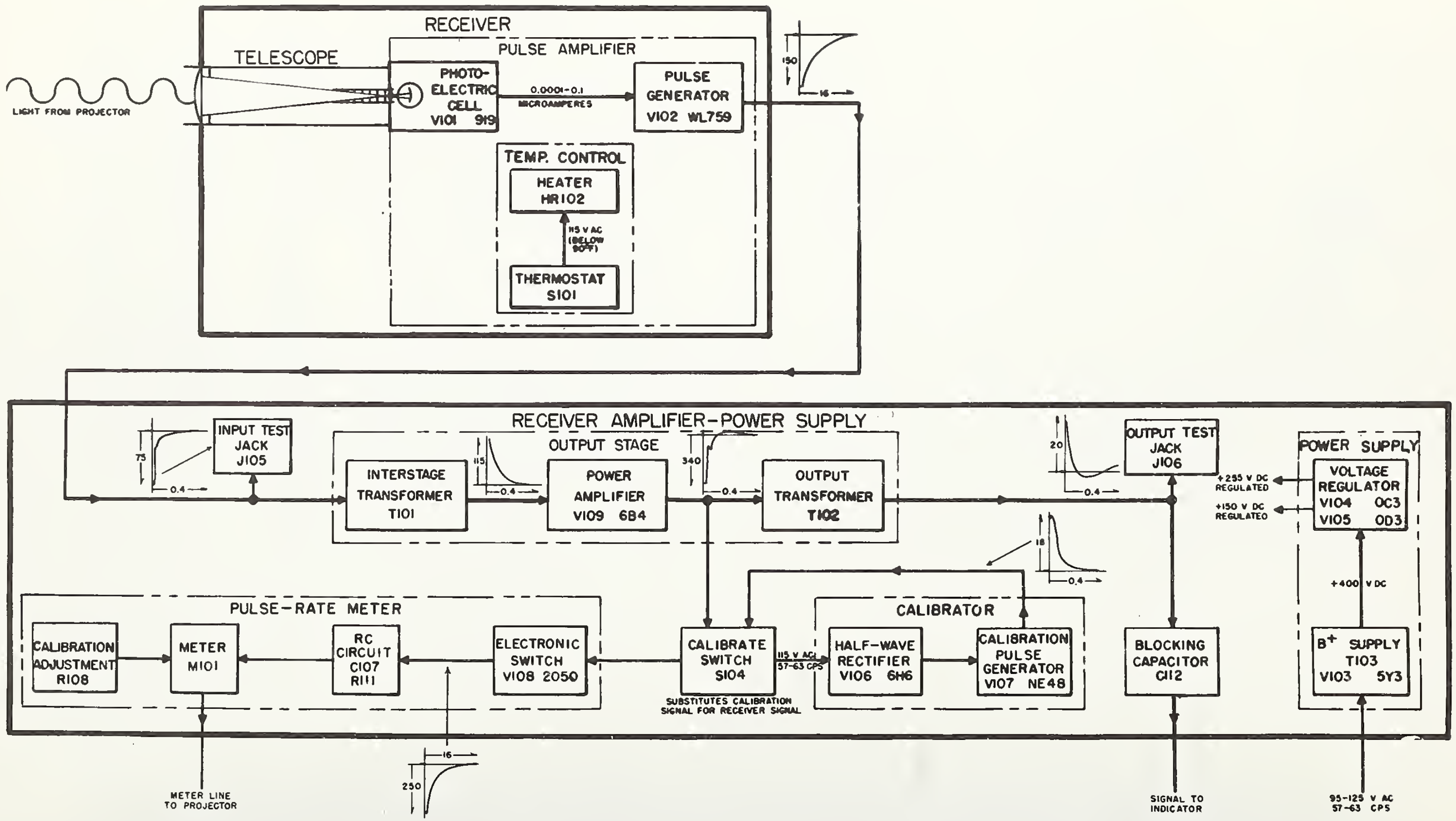


Figure 6.3 Block diagram of transmissometer receiver and receiver amplifier-power supply [103].

to the light falling on the photoelectric cell.

The receiver telescope consists of an objective lens 4 inches in diameter with a focal length of 32 inches. Immediately behind the objective is an iris diaphragm which provides a means of varying the aperture of the system and hence controlling the light flux incident on the photoelectric cell. The light from the projector is focused on the opening in the field stop at the rear of the baffle system (section AA, figure 6.4a). The field stop restricts the field of view of the receiver to approximately 1.2 milliradians (0.07 degree) (half-cone angle) for a 500 foot baseline transmissometer and 2.2 milliradians (0.13 degree) for a 250 foot baseline instrument. This restricts the size of the field at the projector to an area only slightly larger than that of the projector lamp. This reduces the illumination received from the background and from scattered light from the projector itself. A secondary lens is placed immediately behind the field stop. This lens forms an image of the objective lens on the sensitive surface of the photoelectric cell. This is done so that the position of the spot of light on the photoelectronic cell does not change with changes in receiver alignment. This lens also provides a seal between the pulse-amplifier unit and the telescope tube.

The set of baffles mounted ahead of the field stop in the tube at the front of the pulse amplifier reduces further the stray light in the system. The baffles are so arranged that light entering the telescope from most directions other than axially must be reflected several times in order to reach the photoelectric cell. The baffles and the interior of the telescope are finished with a dull black paint so that a high percentage of the light is absorbed at each reflection. A protective hood is mounted in front of the lens to protect the lens from dirt and to reduce the amount of stray light entering the system.

Two heaters and a blower are provided to keep the objective lens free of condensation and the hood free of snow.

The image of the projector lamp will not fall in the center of the opening in the field stop of the receiver telescope system as shown in figure 6.4a unless the center of the projector lamp, the center of the objective lens, and the center of the field stop all lie

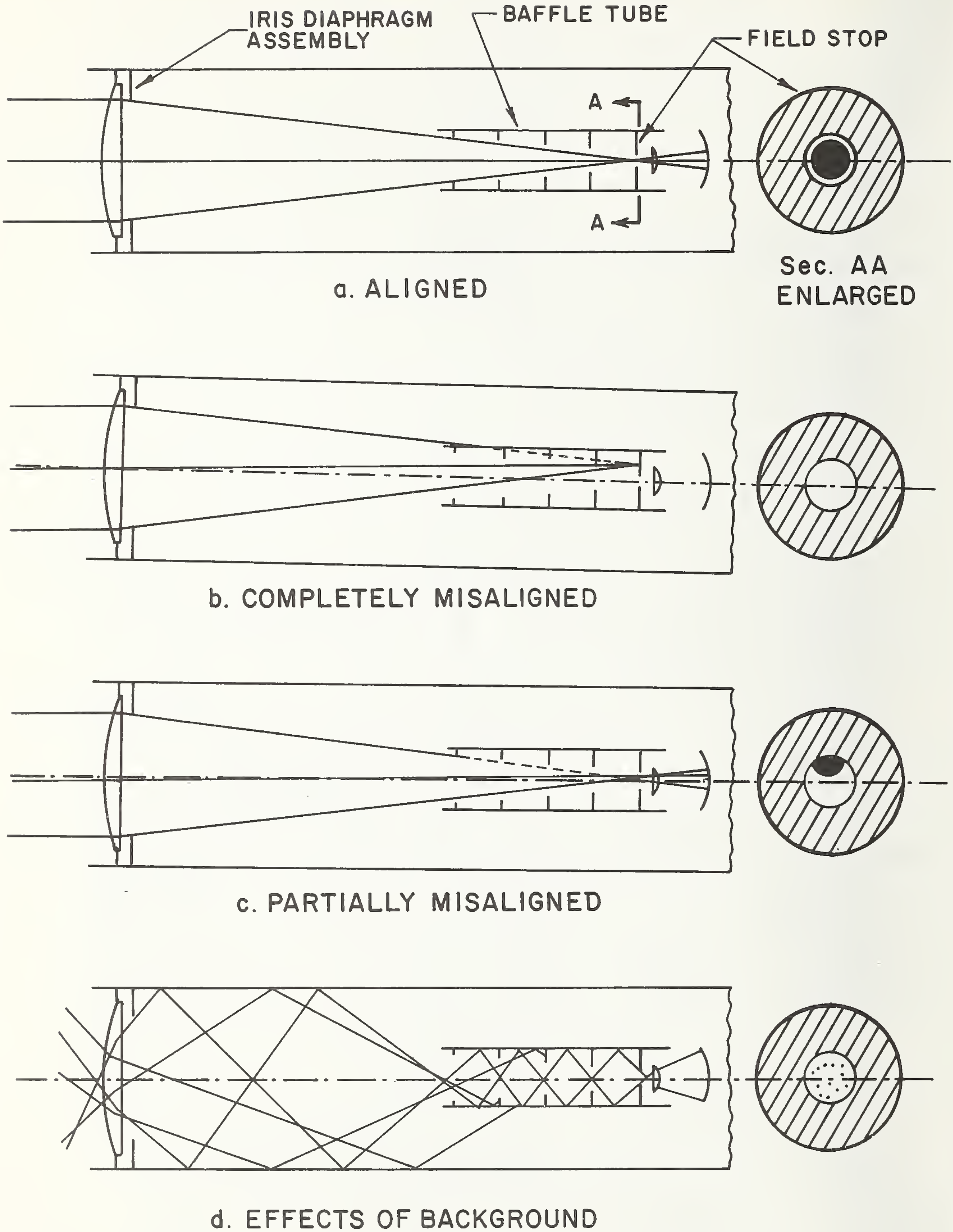


Figure 6.4 Alignment of the receiver telescope.

on the same straight line. This condition is obtained by shifting the position of the field stop with respect to the line through the centers of the lamp and the lens by means of alignment screws at the rear of the telescope. When the image of the projector lamp falls in the center of the opening of the field stop as shown in figure 6.4a, small changes in alignment with the resulting small changes in the position of the image will not affect the light falling on the photoelectric cell as long as the edge of the image does not touch the edge of the opening in the field stop. When the field stop cuts the image of the lamp as shown in figure 6.4c, any slight change in alignment and, hence, in the position of the image, will change the light falling on the photoelectric cell and consequently will alter the transmittance reading. No stand can be made completely stable, because of the effects of small ground movements with changes in soil conditions and the effects of non-uniformities in stand temperature produced by solar heating. Hence, the opening in the field stop is made sufficiently larger than the image of the projector lamp so that the ordinary small shifts in alignment do not cause the field stop to cut the image.

6.1.3.2 Pulse Amplifier

THEORY OF OPERATION. A stable light source and a sensitive, linear, and stable pulse amplifier are the prime requirements of the NBS transmissometer. Therefore the theory of operation of the pulse amplifier and its interaction with the projector will be analyzed in detail.

The pulses in the receiver are generated in the following way (see figure 6.5). The current from the phototube, V101, charges capacitor C101 raising the potential of the starter anode of the trigger tube, V102, to about 160 volts where an arc discharge is initiated in this tube. During the discharge the grid potential decreases to about 100 volts, partially discharging capacitor C101. When the discharge through the tube is extinguished, by the action of R102, the current from the phototube again starts charging C101 and the process is repeated. The time of discharge is very small, 10 microseconds, in comparison to the time of charge, 15 milliseconds, or more.

The constancy of the voltage change across capacitor C101 for

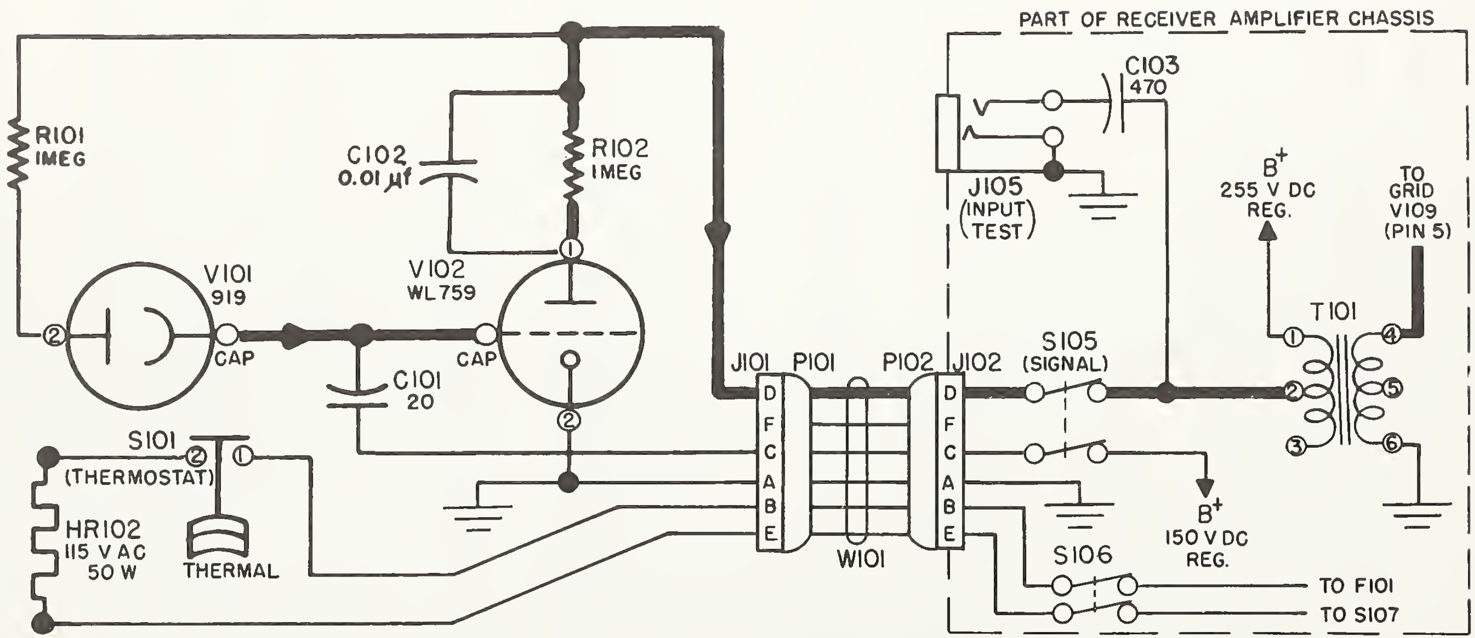


Figure 6.5 Schematic diagram of pulse amplifier and associated components [103].

each discharge is determined by the trigger tube V102. At pulse rates slower than about 5 pulses per minute, the voltage change is usually constant within the limits of measurement. At higher rates there is sufficient variation in this voltage drop from discharge to discharge to produce a noticeably erratic pulse rate in some tubes. It has been found, however, that the voltage change when averaged over a number of pulses is constant and does not change significantly with the pulse rate. The grid voltage necessary to initiate a discharge in the trigger tube is a function of the plate voltage of the tube. There is a range of plate voltage in the region of 255 volts in which the grid voltage required to initiate the discharge is independent of the plate voltage. The plate voltage of the trigger tube is therefore regulated at 255 volts by voltage-regulating tubes in the receiver amplifier.

To reduce the leakage currents over capacitor C101, the capacitor is molded of a high-resistance red bakelite. To reduce the surface leakage over the bakelite, it is coated with ceresin wax. In addition, the low side of the capacitor, which would ordinarly be connected to ground, is kept at a potential of 150 volts. Thus the average voltage difference across the capacitor is approximately -20 volts instead of 130 volts. The envelopes of the phototube and of the trigger tube are also treated with ceresin wax to reduce the effects of humidity on the leakage over the glass surfaces. The connection between the anode of the phototube, the starter anode of the trigger tube, and the high side of the capacitor C101 is supported by the tubes themselves so that leakage to ground can occur only over the envelopes of these tubes and the case of the capacitor.

A second type of leakage is the leakage within the envelopes of the tubes themselves. In photoelectric cells this leakage generally produces a current across the tube even when the tube is dark and less frequently produces a leakage of the photoelectric current to ground. In the first case, the pulse amplifier will continue to pulse at a low rate (one pulse in 10 seconds or slower) when the receiver is dark. In the second case the pulse amplifier may stop pulsing when the light on the photoelectric cell is reduced to that level for which the pulse rate should be one pulse per second or less. Leakage within the trigger tube generally produces the same effect as described for the second case above. In the transmissometer set, tubes V101 and V102 are so selected that the "dark current" of the photoelectric cell will not produce a pulse rate faster than one pulse per minute and the internal leakage of the two tubes is small enough that pulse rates as low as one pulse per minute can be obtained as the light on the photoelectric cell is reduced sufficiently. Using especially selected tubes, well cleaned, a receiver can be operated with photoelectric currents of the order of 2×10^{-12} ampere corresponding to a pulse rate of one pulse in 15 minutes when the capacitance of C101 is 20 picofarads.

TEMPERATURE CONTROL. To reduce the effects of temperature upon the sensitivity of the tubes, a thermostatic switch and a heater operating on line voltage are installed in the receiver.

LINEARITY. The time required to produce a given change in the voltage across capacitor C101 varies inversely with the current through the phototube. Therefore the degree to which the pulse rate is proportional to the flux incident on the phototube depends upon the following factors: (1) the degree of proportionality between the phototube current and the flux incident upon its cathode, (2) the leakage currents, (3) the constancy of the change in voltage across capacitor C101 for each discharge, and (4) the degree to which the time of discharging is negligible as compared to the time of charging capacitor C101. The phototube is of the high-vacuum type and is operated at a voltage sufficiently above the saturation voltage (the minimum voltage across the tube being approximately 75 volts) that the photocurrent is proportional to the incident flux and is substantially independent of the applied voltage. The treatment with ceresin wax and the selection of tubes reduces the leakage current to a low value. The time for discharge of capacitor C101 is less than one thousandth of the time of charge, and Trigger tube V102 is operated at a voltage which produces stable operation. (A detailed discussion of errors in the photometric system is given in Section 6.3.)

STABILITY. It will be noted that the circuitry of the pulse amplifier of figure 6.5 differs from that of figure 6.1. The type 929 phototube of the first transmissometer was replaced with a type 919 phototube to obtain greater stability and lower leakage and dark currents. (The type 919 phototube was later superceded by a special tube designed for the transmissometer which is a variant of the type 919.) The neon lamp, type Ne-2, which was the pulse generator of the first transmissometers was replaced by the type WL-759 for several reasons. Careful and tedious selection was required to obtain neon lamps of sufficiently high leakage resistance. The drift in sensitivity of the neon lamp was greater. Illumination of the electrodes of the neon lamp was required in order to obtain a stable pulse rate. Very careful adjustment of this illumination was required to obtain the stable pulse rate without producing an excessive leakage current. The type WL-759 uses a trace of radioactive material to obtain a stable pulse rate. This tube had previously been used as a photoelectric integrator at slow pulse rates by Nottingham [105] and by Kuper, Brackett, and Eicher [80], but not at the low photoelectric currents or the pulse rates of the transmissometer.

6.1.3.3 Amplifier-Power Supply.

The amplifier-power supply (figure 6.3) for the receiver provides regulated B+ for the pulse amplifier, and amplifies the pulse signal for transmission to the indicator. A metering circuit which measures the pulse rate is included to facilitate alignment and calibration adjustments of the receiver and the projector.

6.1.4 Indicator and Recorder (See Figure 6.6)

6.1.4.1 Amplifier

The indicator contains a two-stage amplifier, a pulse-rate measuring system, and a calibrator providing pulse rates of line frequency and one-fifth line frequency. Before being sent to the metering stages, the pulse signal is amplified by a two-stage, resistance-capacitance-coupled voltage amplifier. This amplifier is designed to improve the signal-to-noise ratio of the pulse signal by providing greater amplification of strong signals than of weak signals and greater amplification of high frequencies than of low frequencies. Thus the voltage amplifier gain for a 60 Hz signal is 0.04 and the gain for a 20 KHz signal is 9.0.

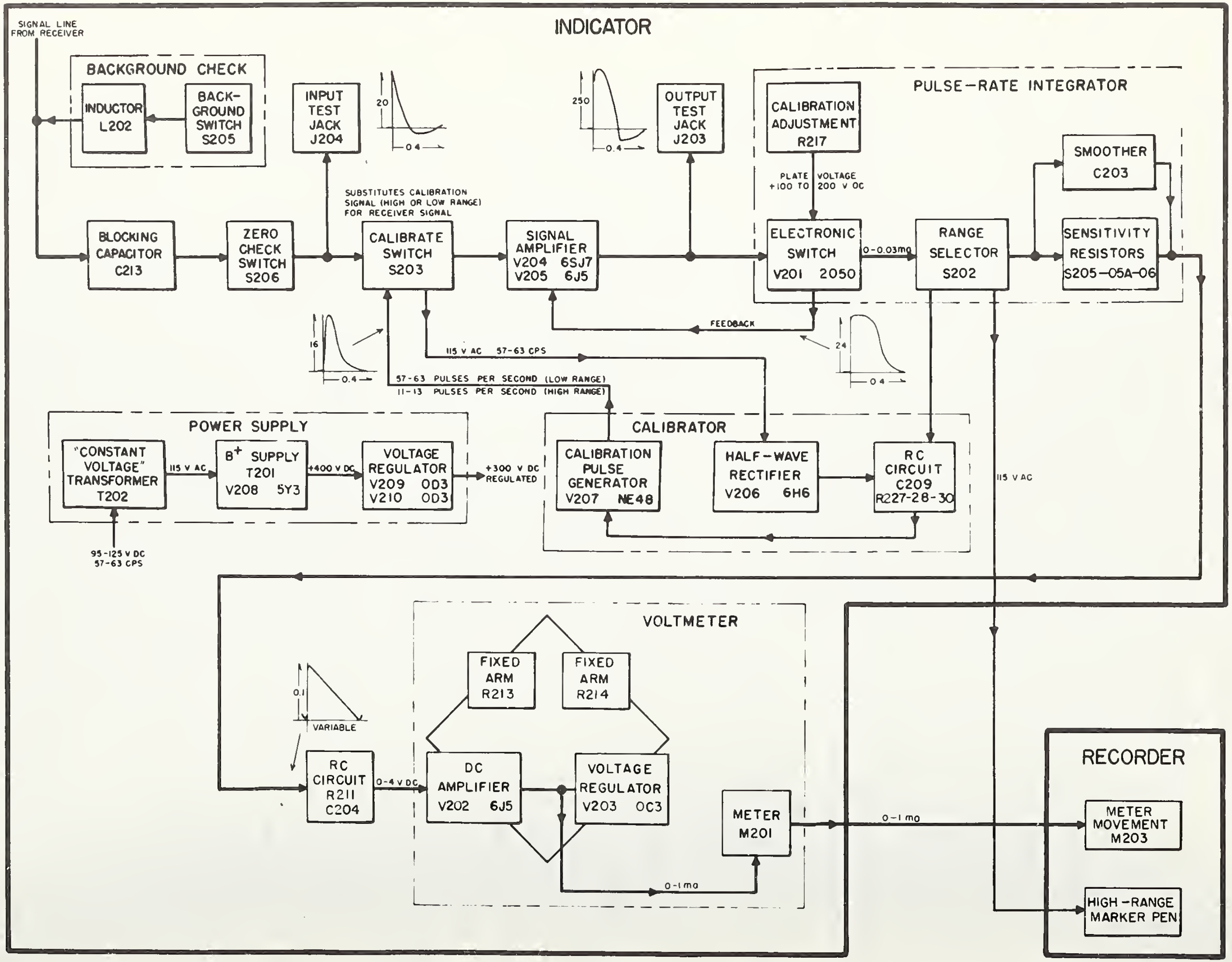


Figure 6.6 Block diagram of transmissometer indicator [103].

6.1.4.2 Pulse Integrator

The pulse integrator consists of a thyratron used as an electronic switch discharging a charged capacitor once, and only once, for each pulse inpressed upon the control grid. This charge is transferred to a smoothing capacitor discharging through a fixed resistor. When the system is in equilibrium, the voltage drop across this resistor is proportional to the input pulse rate and to the value of this resistor. Range changing of the indicator is accomplished by switching resistors.

6.1.4.3 Voltmeter Section

In order to maintain linearity, the capacitance of the capacitor which discharges through the electronic switch is kept small. (Sec. 6.1.4.6). Hence, the average current flowing through the electronic switch is too small to operate a rugged meter or recorder directly and direct-current amplification is necessary. This is accomplished by the voltmeter section which operates from the voltage signal produced by the current through the electronic switch and produces an output current varying between zero and one milliampere. Since this current is proportional to the average current through the electronic switch, it is proportional to the input pulse rate.

6.1.4.4 Calibrator

A calibrator stage is used to provide a pulse signal of a rate equal to the line frequency, (or one fifth line frequency, as desired), for use in correcting sensitivity drifts of the indicator. With an indicator scale graduated 0 to 100, the sensitivity is adjusted so that when a pulse frequency of 60 Hz is applied, a meter reading of 90 is obtained. Since the receiver is adjusted to produce a pulse rate of 60 Hz when the transmittance is 0.90, the indicator meter is direct reading, indicating transmittance in percent.

6.1.4.5 Recorder

A recorder provides a continuous record of the output of the indicator.

6.1.4.6 Indicator linearity and stability

The linearity of the indicator depends primarily upon the degree to which the charge which passes through the electronic switch for each incoming pulse is independent of the pulse rate and upon the degree to which the response of the voltmeter section is proportional to the average current through the electronic switch, and the linearity of the output meter, or recorder. To obtain linearity, the time constant in the electronic switch is kept small in comparison to the minimum time interval between pulses, their ratio being about 0.1, and the voltmeter section is essentially a cathode follower.

6.1.5 Illuminometer

An illuminometer, installed to measure the ambient horizontal illuminance, is used to determine whether the day or night RVR, or RVV, scales should be used. Typically the scale change occurs at an illuminance of 2 footcandles. The illuminometer is usually a simple photoelectrically actuated relay having an accuracy of about 10% in the switching level.

6.1.6 Runway Visual Range Converter

In runway visual range systems the indicator described above is used only as a monitor and a special unit is used to indicate the runway visual range directly. This unit accepts the transmissometer pulse signal either directly from the signal line to the receiver, or, preferably, after the signal has been filtered and amplified by the indicator amplifier, and counts the number of pulses in a fixed time interval in the range 45 to 55 seconds.

The units are essentially memory banks from which the RVR appropriate to: a) a given number of pulses, b) the day or night position of the illuminometer switch, c) the brightness setting of the runway edge lights, and d) the transmissometer baseline, is hooked up and displayed.

6.2 THEORY OF OPERATION

6.2.1 General

The pulse rate of this system is

$$r = i_c/c(E_f - E_d), \tag{6.01}$$

or

$$r = i_c\, S_T/c \qquad (6.02)$$

where

r is the pulse rate in pulses per second.

i_c is the average current, in microamperes, charging capacitor C101 (and the distributed capacitance in parallel with C101) during the charging part of the cycle,

c is the capacitance, in microfarads, of C101 plus the distributed capacitance in parallel with it,

E_f is the potential, in volts, of the starter anode of the trigger tube, V102, at the time a discharge in the tube is initiated,

E_d is the potential, in volts, of the starter anode at the time the discharge is extinguished, and

S_T is the sensitivity of the trigger tube.

Consider first the ideal condition in which the charging current i_c is either equal to i, the current generated in the phototube by the light from the projector, or in which any extraneous currents in the charging circuit are very small in comparison to i. (This is frequently the condition on clear, dark nights.) The photoelectric current is given by the following relation (see figure 6.7).

$$i = (IAS_p\tau/b^2)\, t_b \qquad (6.03)$$

where

I is the intensity, in candles, of the projector,

A is the area of the receiver objective, in square feet, exposed to the flux from the projector,

S_p is the sensitivity of the phototube, in microamperes per lumen, for light of the color temperature of the projector,

τ is the transmittance of the optical system of the receiver,

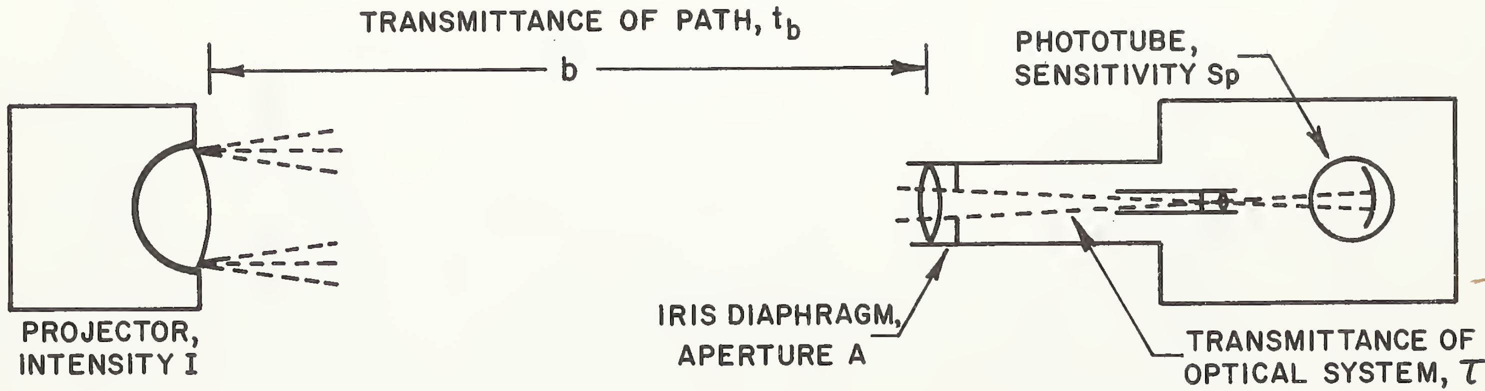


Figure 6.7 Optical path of the transmissometer.

b is the length of the path, in feet, between the projector and the receiver, and

t_b is the transmittance of the path between the projector and the receiver.

Since for the conditions now under consideration i_c is equal to i,

$$t_b = r(cb^2/IAS_pS_T\tau), \tag{6.04a}$$

or

$$t_b = rS \tag{6.04b}$$

where S, the sensitivity of the photometric system is given by

$$S = cb^2/IAS_pS_T\tau. \tag{6.05}$$

It is, of course, desirable that the sensitivity S be adjusted so that the pulse rate of all transmissometers will be the same for any given transmittance. For reasons which will be evident later, a pulse rate of 60 pulses per second has been selected for a transmittance of 0.90 (equivalent to 4000 pulses per minute for a transmittance of 1.00).

Then

$$S = 0.015, \tag{6.06}$$

or

$$cb^2/IAS_pS_T\tau = 0.015, \tag{6.07}$$

and

$$t_b = 0.015r. \tag{6.08}$$

Consider now the factors affecting S. Except for minor changes resulting from cleaning the dirt from the components of the optical system, the transmittance of the optical system, τ, is beyond the control of the operator. The sensitivities of the tubes, S_p and S_T, are characteristics determined during the manufacturer of the tubes and cannot be controlled by the operator except by the selection of tubes. The intensity of the projector, I, is determined largely by the design of the unit but may be varied somewhat by changing the voltage applied to the lamp. The value of the charging capacitor can be varied by changing C101. (Because of the very high leakage resistance which is required, it is not practicable to use a variable capacitor for C101.) The exposed area of the receiver objective, A, can be varied continuously by means of the iris diaphragm. With the exception of the length of the baseline (and possibly the area of the lens opening), it is not feasible to determine the values of the terms on the right hand side of (6.05) to permit the use of this equation in the adjusting of the sensitivity.

Instead S is adjusted empirically by changing the value of one or more of the parameters in (6.07) to obtain the desired pulse rate at a measured or estimated transmittance. Coarse adjustments may be made by changing the lamp intensity, I, or the capacitance of the changing capacitor. Fine adjustments are made by adjusting the exposed area of the objective lens by means of the iris diaphragm.

6.2.2 System Calibration

To facilitate the interpretation of the transmissometer readings, it is desirable that the instrument be adjusted so that, with the indicator on the low sensitivity range, a reading of 100 would be obtained if the air were perfectly clear. Since the air is never perfectly clear, this adjustment can not be done directly. The most frequently used method of making this "100% setting adjustment" is the method of Section 5.1.2.5. With this method, an estimate is made of the visibility at a time when the air is relatively clear and uniform; the transmittance over the transmissometer baseline corresponding to this visibility is determined from appropriate tables or curves based on equation (2.07) using, in the U.S., a value of 0.055 for the contrast threshold. (See Section 3.2.)

In order to overcome the inaccuracies which are inherent in the extrapolation method, the National Bureau of Standards developed (in 1961) a calibrator based upon the principles of Section 5.1.2.4.b [29]. This instrument is a portable photometer consisting of a barrier-layer photocell with a stray-light shield, a telescoping stand for supporting the cell, and battery operated indicating unit using a zero resistance circuit. See figure 6.8.

The design of the instrument is based upon the fact that the atmospheric transmittance can be obtained from the measurement of the illuminance from a reference projector at two different distances if the atmosphere is uniform over the range of distances used. The results are independent of the sensitivity of the receiver and of the intensity of the projector; these quantities need not be known if they remain constant during the calibration.

The transmissometer projector is used as the reference light. A portable photoelectric photometer is used to determine the illuminance at the two distances. The greater of these distances, b, is the transmissometer baseline. The shorter distance, d, is made one-fifth of this distance. These two positions will be referred to as the FAR and the NEAR positions, respectively. The distance to the NEAR position is sufficiently large that the illuminance from the projector follows the inverse square law. The two points of measurement and the projector are colinear. Therefore,

$$E_d = It_d/d^2,$$

and

$$E_b = It_b/b^2.$$

where E is the illuminance, I the intensity, and t_d and t_b are the transmittances over the paths indicated.

These equations can be solved simultaneously for t_b, the transmittance of the transmissometer path, using the relation

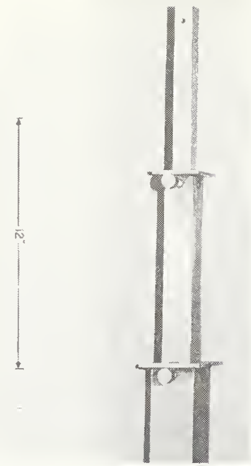
$$t_d = t_b^{0.2}.$$

Therefore,

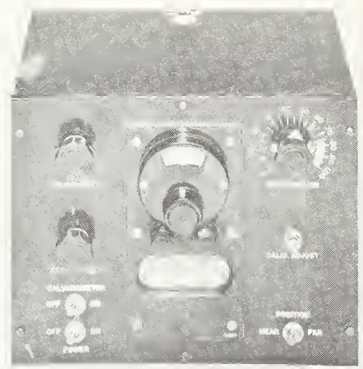
$$t_b = [(E_b b^2)/(E_d d^2)]^{1.25}. \qquad (6.09)$$

In operation the receiver was positioned and aligned at the NEAR

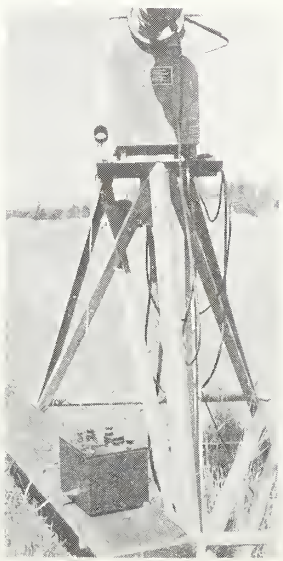
PHOTOCELL WITH SHIELD, SHOWN ON FAR POSITION HOLDER



SECTION OF THE TELESCOPING STAND USED AT THE NEAR POSITION



METERING UNIT



CALIBRATOR AT FAR POSITION

CALIBRATOR AT NEAR POSITION

Figure 6.8. Transmissometer calibrator.

position and the indicator sensitivity adjusted to obtain a fixed reading. The receiver was then moved to the FAR position and the transmittance read directly from a specially calibrated potentiometer scale. (See figure 6.8). With careful operation, the transmissometer 100% setting could be made with an expected uncertainty of about 1.5%.

Calibrators of this type were purchased by the Air Force from a commercial source, but none were purchased for civil use.

The NBS calibrator had some significant deficiencies.

a. The field of view of the receiver was made large so that there would be no alignment difficulties when it was used on a telescoping rod at the NEAR position. As a result the effects of illuminance from the background were so large that the calibrator could not be used during daylight.

b. The illuminance at the FAR position was less than one-twenty-fifth of the illuminance at the NEAR position. This placed severe requirements on the linearity of the instrument and careful laboratory adjustment was required to compensate for any non-linearity.

c. The method requires a stable, uniform atmosphere. Hence it could not be used in fog where temporal and spatial changes were significant. (It could, however, be used in visibilities of the order of one mile (night)).

All of the deficiencies of the NBS calibrator are overcome in the second generation of calibrators. In these calibrators, a laser (developed after the NBS calibrator) is used as a source (Method c of Section 5.1.2.4). The aperture of the receiver is made large enough to accept the entire beam of the laser at the FAR, or receiver, position, as well as at the NEAR, or source, position.

If the receiver is placed at the source and adjusted to read 1.00, it will then directly indicate the transmittance over the transmissometer baseline when it is moved to the transmissometer receiver for

$$\phi_b = \phi_o t_b \qquad (6.10)$$

where

ϕ_o is the laser flux incident on the calibrator when it is at the source, and

ϕ_b is the flux incident on the calibrator when it is at the transmissometer receiver.

Then if the instrument in linear,

$$R_b = R_o t_b \ ,$$

where R_o and R_b are the calibrator readings at the source and receiver, respectively.

When the sensitivity of the calibrator is adjusted so that R_o is equal to 1.00,

$$R_b = t_b .$$

The iris diaphragm of the transmissometer receiver is then adjusted to obtain a reading on the transmissometer the same as that of the calibrator.

In principle, a calibrator of this type could be used under all visibility conditions. However, at high fog densities, accuracy is limited by the meter readouts of the Calibrator and the Amplifier Power Supply. When conventional moving-coil meters are used, these errors may be as large as 0.01. See Section 6.3.3. The relative error in subsequent transmittance measurements is given approximately by

$$\Delta t/t_b \approx (\Delta R_b + \Delta R_A)/R_b \qquad (6.11)$$

where

ΔR_b is the error in reading the Calibrator meter,

ΔR_a is the error in reading the meter of the Amplifier Power Supply, and

R_b is the calibrator reading, the transmittance over the baseline, at the time of calibration.

6.2.3 Effect of Changes in Baseline

As seen from equation (6.07) the required sensitivity of the transmissometer varies as the square of the length of the baseline. The NBS transmissometer, which uses a PAR 64 type sealed-reflector lamp having a peak intensity of about 140,000 candles when operated at design voltage, was originally designed for use on a 500-foot baseline.

If the baseline is increased, the over-all sensitivity, S, must also be increased in order to maintain a reading of 100 when t_b is 1.00. (For a 750-foot baseline, the sensitivity must be more than double that required for a 500-foot baseline.) This increase in sensitivity can be accomplished by decreasing the capacitance of C101, by operating the lamp at somewhat above design voltage, by using tubes of higher than average sensitivity in the pulse amplifier, or by changing the indicator sensitivity so that a greater reading is obtained for a given pulse rate. If the baseline is not longer than 750 feet, changes in the capacitance of C101 are usually sufficient. However, the increase in sensitivity which can be obtained by this means is limited. Therefore, if the baseline is longer than 750 feet, other methods of increasing the system sensitivity must be used. Since, as indicated by equation (6.19), increasing the length of the baseline results in an increase in the background reading unless the intensity of the projector is increased, the change in system sensitivity is usually accomplished by increasing the intensity of the projector. This requires the use of projectors of larger aperture than the PAR 64 lamp used in the regular projector. Projectors using precision parabolic reflectors and 250-watt, 12.5-volt, C-8 filament, projection lamps have been satisfactory. The lamp is usually operated at a voltage which will give a lamp life of about 1000 hours. The recommended maximum lengths of baseline for projectors of various apertures are given in table 6.1.

Table 6.1

Reflector Aperture Required for Several Baseline Lengths

Reflector Aperture (inches)	Recommended Maximum Baseline (feet)
12	1500
18	2500
24	4000

Baselines longer than those listed in table 6-1 may be used if the indicator sensitivity or the receiver aperture is increased and careful attention is given to the background correction. The sensitivity of the indicator may be readily increased by simple circuit changes so that, instead of obtaining a reading of 1.5 when the pulse rate is one per second, a reading of 15 or more is obtained. On the other hand, increasing the aperture of the receiver would require rebuilding of the receiver telescope.

Conversely, when baselines shorter than 500 feet are used, the sensitivity requirements of the instrument are less severe. The reduction in sensitivity can be obtained by using any of the following singly or in combination:

1. An increase in the value of C101, thereby decreasing the sensitivity of the receiver. This is the preferred method since it also reduces the effects of both background illumination and leakage currents.

2. Reduction of light source intensity by operation at a lower voltage. Such a reduction will increase lamp life significantly and may be used in combination with method 1. Redesign of the instrument to use a smaller lamp is not desirable since the effects of background and leakage would not be reduced.

3. Reduction of the receiver aperture either by closing the diaphragm or redesigning the optical system of the receiver. This method would reduce the effects of background illumination but not the effects of leakage currents, and, hence, is not as desirable as method 1.

4. Use of phototubes (V101) and trigger-tubes (V102) of lower sensitivity. This method has the same effects as method 3, and, hence, does not appear desirable. However, some tubes of the types now in service, not satisfactory for 500 or 750 foot baselines, would be acceptable when using baselines shorter than 500 feet.

6.2.4 Methods of Modifying the Transmissometer System to Permit Its Use During Periods of Very Low Runway Visual Ranges

This section is a brief updating of reference [26].

As aircraft landing minimums are reduced, the transmissometer pulse rate becomes a limiting factor during periods of low visibility. For example, the minimum pulse rate with a 250 foot baseline transmissometer for the range of transmittances reported as a nighttime RVR of 600 feet is about one pulse in 5 seconds, assuming a reporting interval of 100 feet and, therefore, an actual RVR of 550 feet.

Therefore, if RVR's lower than 600 feet are to be reported, some modification of the transmissometer-RVR converter system is required. The following methods of modifying the system are analyzed in this report.

1. Increase in length of time interval in which pulses are counted by the converter.
2. Modifications of the RVR converter to measure the time interval between pulses.
3. Increase in the pulse rate of the transmissometer by increasing its sensitivity.
4. Reduction of the length of the baseline.

Figures 6.9 and 6.10 have been prepared to assist in the interpretation of the effects of these modifications. Figure 6.9 shows the relation between transmittance and RVR as a function of the length of the baseline. In preparing this figure an intensity of 10,000 candles and a threshold illuminance of 2 mile candles have been assumed in computing the RVR. These curves represent nighttime operation with the lighting system at full intensity. Figure 6.10 shows the relation between seconds per pulse and RVR as a function of length of the baseline. It was prepared from the data of figure 6.9 assuming a pulse rate of 4000 pulses per minute for a transmittance of 1.00.

It is apparent from the figure that the reduction in minimum RVR*

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*The RVR's referred to in this discussion are the actual minimum RVR's which could be indicated. Thus they are the lower limit, not the center, of a reportable interval.

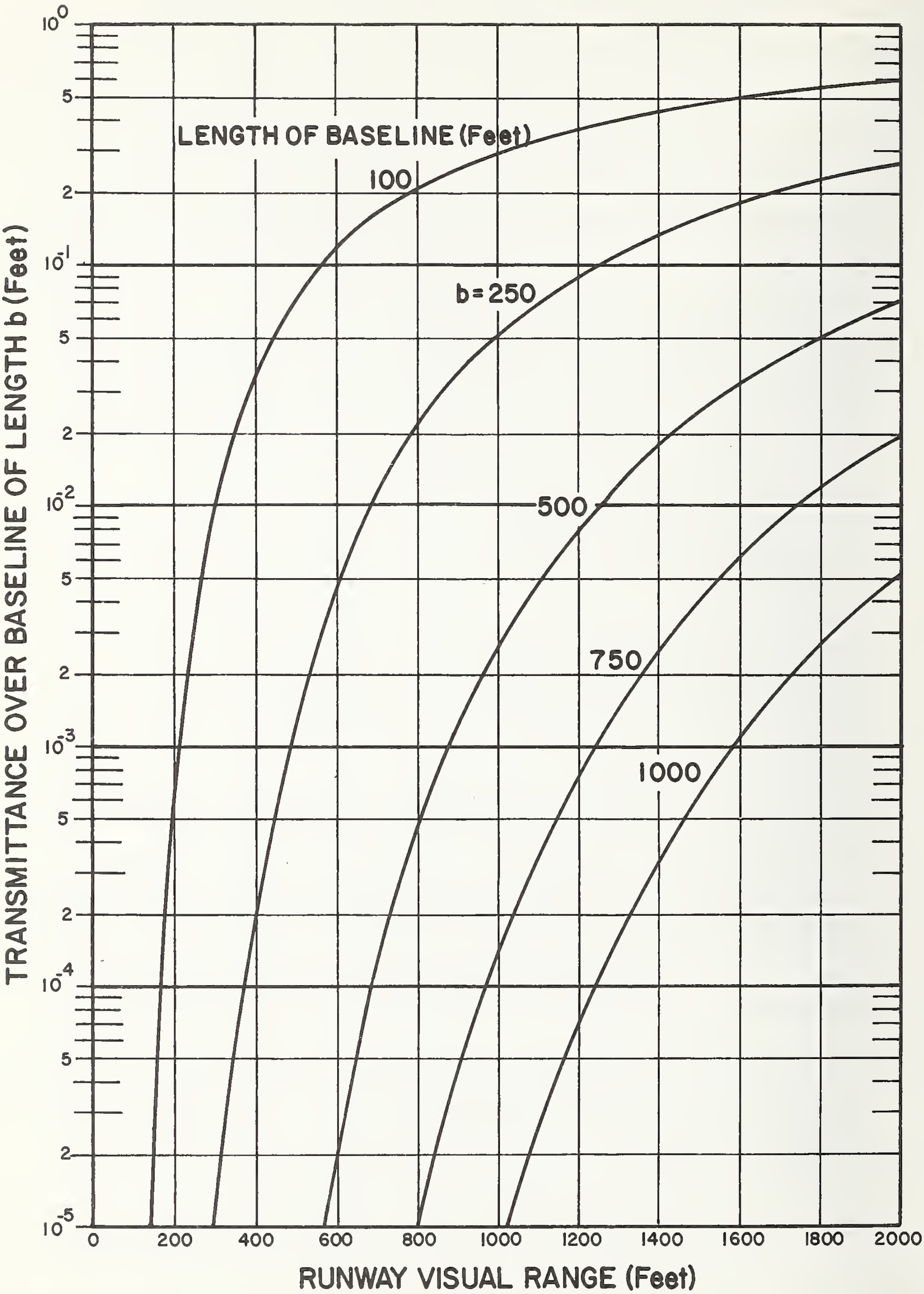

Figure 6.9 Transmittance as a function of RVR (night-step 5) for several lengths of baseline.

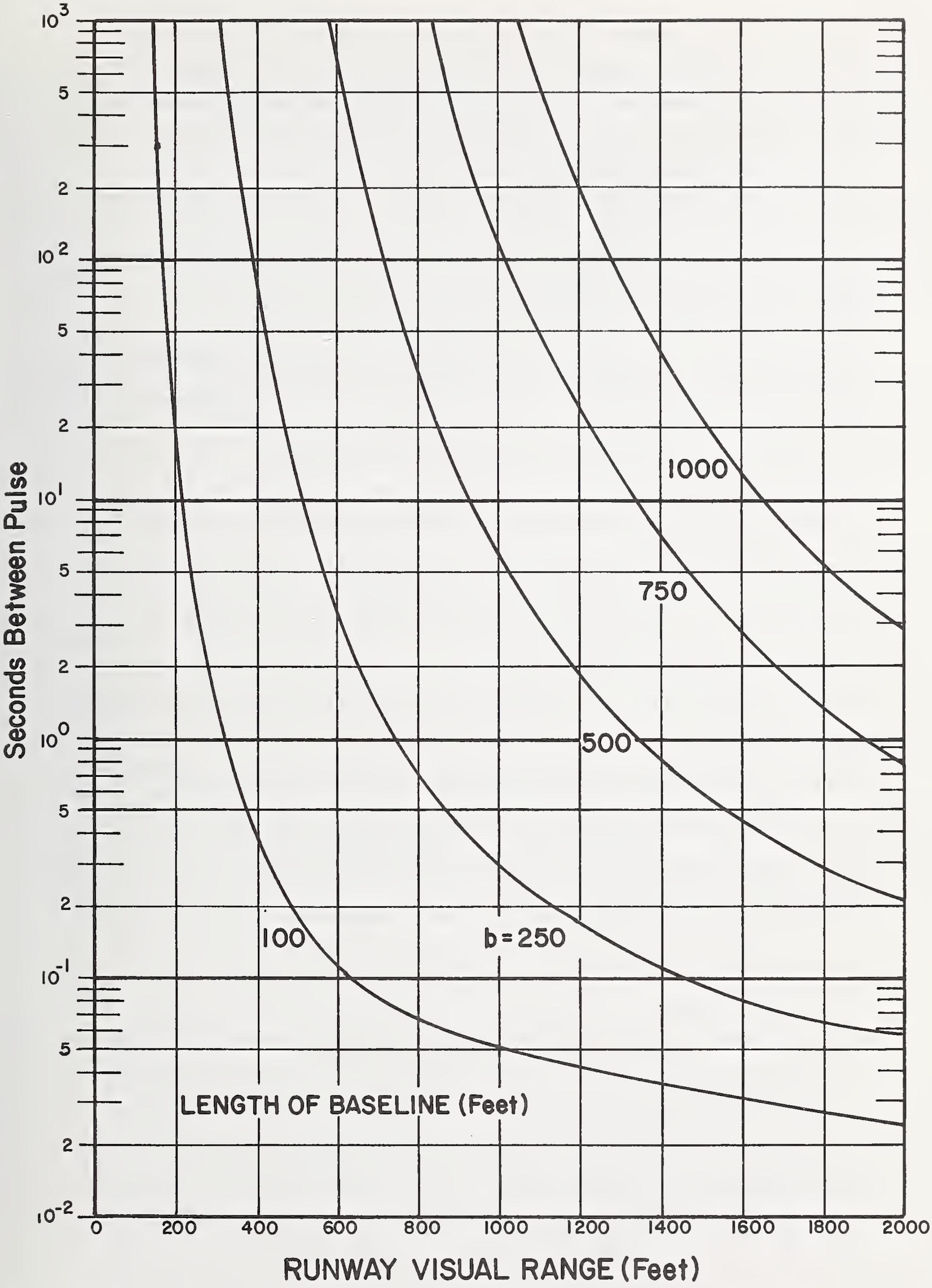

Figure 6.10 Pulse period as a function of RVR (night-step 5) for several lengths of baseline.

which can be accomplished by increasing the length of the time interval during which pulses are counted is very limited. For example, with a 250 foot baseline transmissometer, changing the counting time from 1 to 5 minutes would reduce the minimum measurable RVR from 480 to 400 feet.

Similarly modifying the RVR converter to measure the time interval between pulses would be only a little better. A pulse interval of 100 seconds would be required to obtain an RVR of 400 feet. Increasing transmissometer sensitivity would be more satisfactory.

An increase in sensitivity of the present 250 foot baseline transmissometer by a factor of 10 is feasible. This increase would reduce the minimum RVR to 350 feet. The pulse rate corresponding to a transmittance of 1.00 would then be 40,000 pulses per minute.

Greater increases in sensitivity could, of course, be obtained with a complete redesign of the instrument. However, to obtain a minimum RVR of 200 feet, corresponding to a transmittance of 6.6×10^{-9} over a 250 foot baseline, a pulse rate of 1.52×10^{8} pulses per minute would be required, assuming a minimum permissible pulse rate of one pulse per minute. Transmission of pulses at this rate would require coaxial transmission lines.

Shortening the baseline will produce a significant increase in the pulse rate in very dense fogs as is demonstrated by figures 6.9 and 6.10. The lower limit of operation as a function of the length of the baseline is summarized in table 6.2.

Table 6.2

Minimum Measurable RVR of Present NBS Transmissometer and RVR Converter as a Function of Length of the Baseline

Length of Baseline (feet)	Minimum Measurable RVR in the Reportable Value (feet)
1000	1700 (1)
750	1300 (1)
500	900 (1)
250	500 (1)
100	220 (1)
50	120 (1)
250	360 (2)
100	170 (2)
50	90 (2)

(1) Based on a pulse rate of 4000 pulses per minute when $t_b = 1.00$

(2) Based on a pulse rate of 40,000 pulses per minute when $t_b = 1.00$

Note: In computing the lowest reportable RVR, a 200 foot increment is assumed for RVR's of 1000 feet and higher. A 100 foot increment is assumed for RVR's below 1000 feet. Thus, RVR's in the interval 900 to 1100 feet would be reported as an RVR of 1000 feet.

The primary difficulties involved in the use of a shorter baseline are the reduction in the length of the sample measured and the decrease in the maximum RVR which can be indicated with satisfactory accuracy. There are several possible methods of compensating, at least in part, for these difficulties; Among these are: (1) the use of two transmissometers "end-to-end", (2) the use of a dual-baseline transmissometer, and (3) the use of a composite baseline transmissometer.

If two transmissometers are installed with their baselines end-to-end and their outputs combined so that the product of the two transmittances is indicated, the problem of decreased length of sample will be eliminated. It should be noted that the two transmissometers need not be located so the two baselines form a continuous line. The two baselines need not, and should not, be precisely colinear. A deviation of several degrees in the orientation of baselines is desirable to reduce the effects of the light source of one on the receiver of the other. Nor are the two baselines required to be so located that one starts where the other ends. An interval as long as one or two baselines may be left between the end of the first baseline and the start of the second. This procedure would require a more complex computer than is now used.

Another means of improving the sampling is the use of a dual-baseline transmissometer, that is, two receivers at different distances from a projector. A switch-over device would be included so that the longer baseline is used whenever the fog density is such that operation with this baseline is feasible. (Such instruments were used in the initial transmissometer installation at Nantucket and also at the Landing Aids Experiment Station.) Because of the limited field of view of the receiver, the use of two receivers with a single projector is preferable to the converse. Although this method requires less instrumentation and would be less costly than the "end-to-end" transmissometers, it is considered less desirable for the following reasons:

(a) During periods when use of the short-baseline section is required, a less adequate sample of fog is used with this method.

(b) This method provides a less satisfactory means of indicating the variations in a non-homogeneous fog.

(c) There is no redundancy in the instrumentation during periods when the use of the short baseline is required. The only redundancy in good weather (when the long baseline should be used) is the possibility of using the short baseline should the long-baseline receiver fail.

This method would, however, provide more accurate RVR indications for the higher RVR's than would the "end-to-end" transmissometers. If the length of the "long" baseline is made more than 250 feet, this method would provide higher accuracy during periods of high RVR's than does the present 250 foot instrument. It should be noted that, if the "long" baseline is increased to more than 750 feet, a projector of higher intensity than the present projector would be required unless a more sensitive receiver is used.

A composite baseline transmissometer is similar to a double-baseline instrument using two projectors, except that in this instrument the two projectors are operated simultaneously. The primary advantage of this system is that no switch-over between baselines is required. However, its accuracy would be inferior to that of a double-baseline instrument for all RVR's.

Note: A careful study should be made of the frequency of very low RVR's before a choice is made of the method of modification. NBS experience at Arcata indicates that very dense fogs are surprisingly infrequent. During a three year period, no RVR's below 300 feet were observed and there were only 26 minutes during which the RVR was in the 300-400 foot range [25a].

6.3 ERRORS IN THE PHOTOMETRIC SYSTEM AND THEIR EFFECTS ON THE INDICATED VISIBILITY

6.3.1 General

Consideration will now be given to the errors in the photometric system and to the effect of these errors on the measurements of transmittance and on the indicated visibility.

As previously shown, by day the indicated visibility, V, is obtained from Koschmieder's Law, which may be written as

$$(V/b) \ln t = \ln \varepsilon^{*} \quad (5.10)$$

where ε is the contrast threshold of the observer;
and from this it follows that, if Δt is small,

$$\Delta V/V = -(V/b)(1/\ln \varepsilon)(\Delta t/t). \quad (5.09b)$$

Therefore, the relative error in the indicated visibility is proportional to the ratio of the indicated visibility to the length of the baseline. Hence, if reasonable accuracy is to be obtained in the indicated visibility in clear weather, the requirements of instrumental accuracy for short baseline transmissometers are very stringent. For example, when the day visibility is about 10 miles, instrumental errors of 0.15% and 0.3% with 250 foot and 500 foot baseline transmissometers, respectively, will produce an error of 10% in the indicated visibility. On the other hand, when the day visibility is about one quarter mile, instrumental errors of 5.5% and 11% are required to produce an error of 10% in the indicated visibility.

The analysis which follows is based upon NBS tests and analyses [28] and performance tests conducted at NAFEC by Hochreiter and McCann [44].

Whenever possible, quantitative statements of errors of the latter study are used as the instruments used in this study are considered more representative of instruments now in service than those used in the earlier NBS studies, since some of the electronic components and circuitry have been modified over the years. There are, however, no significant, or unexplainable, differences between the NAFEC and NBS data.

The analysis is based upon the performance of a transmissometer whose components are operating properly and which meets the performance criteria of Section 6.5 of reference [103], given in Appendix D. Note that the requirements stated are <u>minimum</u> requirements (maximum errors), not representative values.

The errors in the transmissometer may be conveniently divided into two general classes: (1) those in which Δt is constant and independent

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* For the sake of clarity, the subscript b is omitted through this Section.

of transmittance; and (2) those in which the error, Δt, in the transmittance measurement is proportional to the transmittance. Since the sources of these errors and their effects on the indicated visibility differ, the two classes will be considered separately.

6.3.2 Constant Incremental Errors.

Consider now the effect of errors which are independent of the transmittance of V, that is, Δt is constant. Equation (5.09b) may be written as

$$\Delta V/V = \Delta t/(t \ln t). \qquad (6.12)$$

The quantity $t \ln t$ approaches zero as t approaches zero and as $\ln t$ approaches zero (t approaches one). Hence the relative error in the indicated visibility produced by a constant Δt will become large in either very foggy weather or in very clear weather. This effect is illustrated in figure 6.11 where the indicated visibility corresponding to transmittances equal to $t \pm \Delta t$ is plotted against the indicated visibility corresponding to the transmittance, t. Figure 6.11 is directly applicable to a 500 foot baseline transmissometer. It may be applied to transmissometers of other baselines by multiplying the coordinates of the visibility scales by 0.002 times the length of the new baseline.

It may be easily shown, by differentiation of (6.12) with respect to t, that the effect of constant errors is a minimum when the transmittance of the path b is 37 percent. The corresponding daylight visibility is 0.3 mile when a 500 foot baseline is used. See Section 5.4.

Sources of constant errors are (a) extraneous currents in the charging circuit of the pulse amplifier, resulting from dark current, leakage current and from illumination of the phototube by light from the background, and (b) reading out errors. These will now be considered in detail.

The extraneous currents are independent of the atmospheric transmittance and produce relatively constant errors.

The charging constant in the pulse amplifier, i_c, is the sum of the following:

$$i_c = i + i_s + i_d - i_L \qquad (6.13)$$

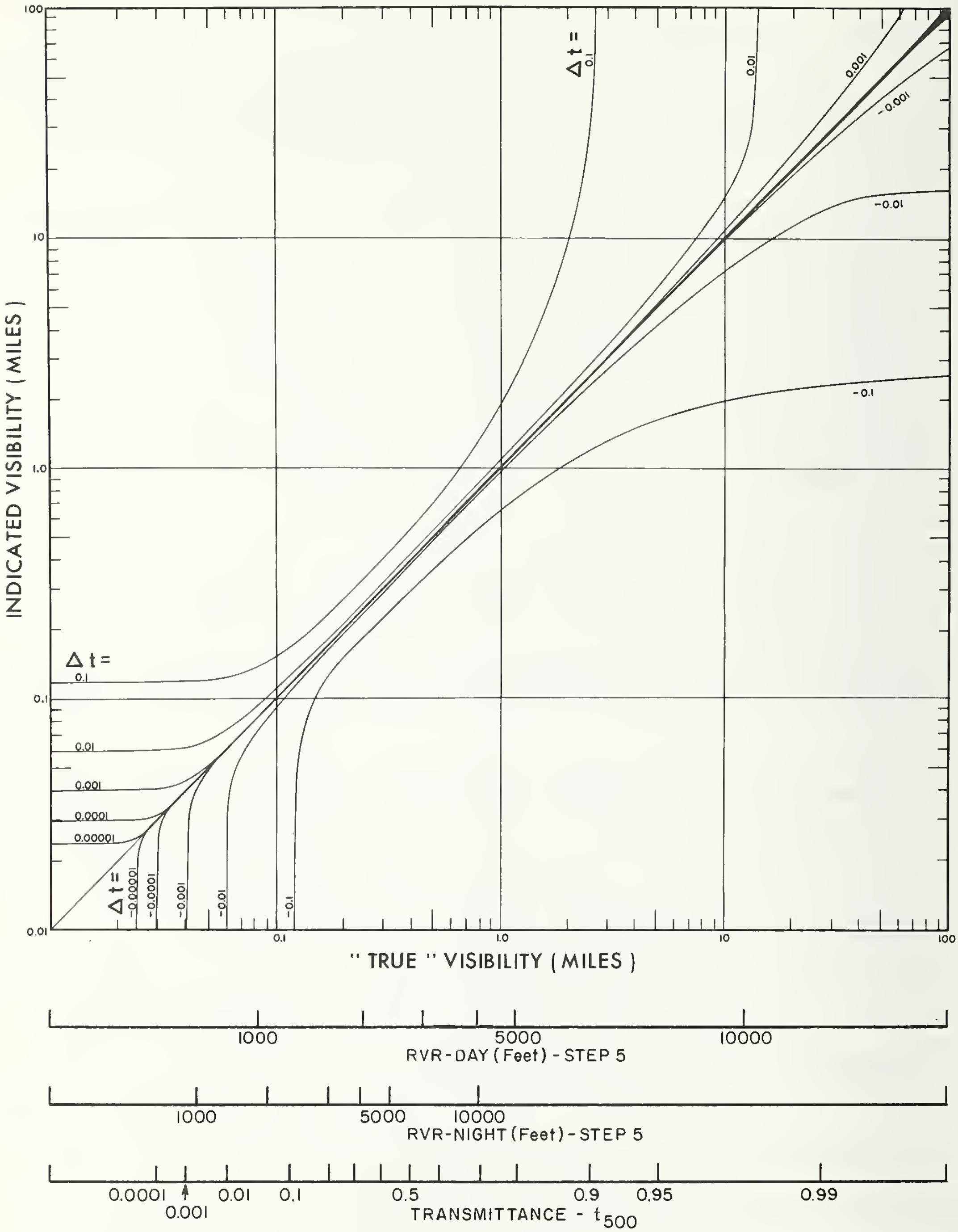

Figure 6.11 Effects of constant incremental errors in transmittance measurements on the indicated daytime visibility. Also shown are associated daytime RVR and transmittance scales. Although shown only on the abscissa, these scales also apply to the ordinate. All computations are based on a 500 foot baseline.

Where i is again the current of the phototube generated by the light from the projector,

i_s is the current of the phototube produced by the light from the terrain or the sky behind the projector,

i_d is the dark current of the phototube (Note that i_d will be negative if the leakage between the cathode of the tube and ground exceeds the leakage current between the cathode and the anode.),

i_L is the leakage current across C101 and from the grid of the trigger tube V102 to ground.

If i is i_o when t is unity, then

$$t = i/i_o.$$

Let t' be the apparent transmittance.

Then

$$t' = i_c/i_o, \tag{6.14}$$

and, since

$$t' - t = \Delta t,$$

$$\Delta t = (i_s + i_d - i_L)/i_o, \tag{6.15a}$$

or

$$\Delta t = \Delta t_s + \Delta t_d - \Delta t_L \tag{6.15b}$$

where

$$\Delta t_s = i_s/i_o,$$

$$\Delta t_d = i_d/i_o,$$

and

$$\Delta t_L = i_L/i_o.$$

If the sum i_s and i_d is greater than i_L, the receiver will generate pulses at a rate proportional to Δt when the projector is turned off. The incremental error, Δt, is then numerically equal to the transmittance corresponding to this reading. No pulses will be generated with the projector off when Δt is negative. Instead, the instrument will indicate a transmittance of zero for all values of t which are numerically less than Δt.

6.3.2.1 Errors produced by background illumination.

During daylight hours i_s is usually large in comparison to either i_d or i_L. From equation (6.03) we have

$$i_o = IAS_p\tau/b^2. \tag{6.16}$$

Hence

$$\Delta t_s = i_b b^2/IAS_p\tau. \tag{6.17}$$

The photoelectric current generated by the light from the background is given by

$$i_b = \Psi^2\ LAS_p\tau \tag{6.18}$$

where ψ is the half angle of the field of view of the receiver in radians and

L is the average luminance of the background within this field, in candelas per square foot.

Therefore

$$\Delta t_s = \psi^2\ Lb^2/I. \tag{6.19}$$

The performance requirements of Appendix D limit the pulse rate caused by background illumination to one pulse per second, corresponding to a Δt_s of 0.015. To obtain this low value, ψ is made as small (about 0.0022 and 0.0013 radian (half-cone angle) for 250 foot baseline and 500 foot baseline transmissometers respectively) as is consistent with the stability of the receiver mounting; wherever possible the receiver is so oriented that L will be as low as possible; and a projector having a suitably high intensity is used. Note that when the length of the baseline is increased, the projector intensity must be increased as the square of the length of the baseline, if Δt_s is to be kept constant.

6.3.2.2 Errors produced by dark and leakage currents.

At night the phototube dark current, i_d, and the leakage current, i_L, are usually greater than the background current, i_s. Substituting from (6.16), we have

$$\Delta t_d = i_d b^2/IAS_P\tau , \qquad (6.20)$$

and

$$\Delta t_L = i_L b^2/IAS_P\tau . \qquad (6.21)$$

These equations show again the desirability of using projectors of high intensity and phototubes of high sensitivity. Note that keeping the receiving aperture large will reduce Δt_d and Δt_L but will not effect Δt_s. In order to be able to use the iris diaphragm at nearly its maximum aperture, it is often desirable to adjust the sensitivity of the receiver by means of C101 so that the diaphragm must be nearly fully open before equation (6.07) is satisfied.

The performance requirements of Appendix D state that the sum of i_d and i_L produce a pulse rate no greater than one pulse in 30 seconds, corresponding to a Δt_d plus Δt_L of 0.0005.

Since the effects of the phototube dark current and the trigger-tube leakage current are opposite, at first thought matching of tubes appears to be advantageous. However, unless the dark current of the phototube and the leakage current of the trigger tube are very nearly equal, the incremental error, Δt, is not affected significantly. Since both the dark currents and the leakage currents of the tubes of a group extend over wide ranges, it is improbable that tubes with nearly equal extraneous currents can be found. Experience has indicated that the net error resulting from these currents can seldom be made less than one-fifth the error produced by the current of either tube. Therefore, for critical applications, it is essential that the extraneous currents of both tubes be low.

From figure 6.11 it is evident that when the visual range is low, these errors, Δt_s, Δt_d, and Δt_L will not have a significant effect on the indicated visual range until t approaches Δt in value.

When the visibility is high, only Δt_s is sufficiently large to produce a significant error, and this error may be reduced significantly, if desired, by measuring Δt_s with the projector off and subtracting Δt_s from t'.

6.3.2.3 Reading Out Errors

Reading out of the transmittance determined by the transmissometer may be accomplished in two ways: by producing meter deflection which is proportional to the pulse rate, as is done by the indicator; or by timing the pulses. The errors in the use of the indicator will be considered first.

These errors may be conveniently divided into three groups: (1) those resulting from deviations from linearity in the conversion of pulse rate to output current in the pulse-rate integrator and voltmeter stages; (2) errors in the indicating meter or recorder; and (3) errors in the reading of the indication of the meter or the recorder. Repeated tests with signals whose pulse rate is known accurately show that the electronic circuitry is sufficiently linear so that the linearity of the output meter, or recorder, is the limiting factor. These meters usually have a rated accuracy of 0.5% of full scale at any place on the scale. Since the indicator is adjusted to give a reading of 0.90 when the pulse rate is 60 pulses per second, absolute accuracy is not a significant factor, but linearity and repeatability are.

The meter and recorder scales are 50-division scales which can be read easily to one-fourth of a division or 0.5% of full scale. The expected error resulting from both meter inaccuracies and reading errors is, then, about 1% of the full-scale meter reading. Therefore, Δt is about 0.01 when the indicator is on the low sensitivity range and about 0.002 when it is on the high sensitivity range. However, since in making the 100% setting, the over-all sensitivity of the instrument is adjusted so that a full-scale meter reading would be obtained if the air were perfectly clear, errors due to the meter are reduced for deflections near full scale so that the expected error in this region is about 0.005 when the low sensitivity range is used. Since the high sensitivity range is adjusted to five times the sensitivity of the low range when the readings are near full scale, the error in this region is about 0.001 when the high range is used. The curves of figure 6.11 indicate that these errors do not produce significant errors in the indicated visibility except when the visibility is greater than about 5 miles or less than about 0.1 mile, for a 500 foot baseline instrument.

When an RVR converter is used, the counting interval is timed by reference to line frequency. Thus the accuracy of the timing interval is determined by the accuracy to which line frequency is known. The frequency of commercial power sources typically does not differ from line frequency, 60 Hz, by more than 0.05 Hz, and the frequency of engine generators typically is within 1 Hz of line frequency. Thus the errors in the timing interval for commercial power and engine generators are expected not to exceed 0.1 and 1.6 per cent respectively.

There is also a possibility of an error of as much as one count in the number of pulses counted as the number of pulses in a fixed interval is counted not the time for a fixed number of pulses. From equation (6.08) it follows that when pulses are counted for a fixed time interval

$$t = 0.015\ N/Z.$$

where N is the number of pulses counted in the time interval Z, in seconds.

Then

$$\Delta t = 0.015\ \Delta\ N/Z \tag{6.23}$$

As stated earlier ΔN is equal to one. If the counting period, Z, is 50 seconds, Δt is 0.0003.

It is apparent from figure 6.11 that the readout error of the converter is significant only at very low visibilities, where the readout error is, indeed, the factor which determines the lower limit of RVR measurements at night.

Note that if an integral number of pulses is counted, there need be no error in N. With appropriate electronics, the time interval, Z, can be measured easily to an accuracy much better than required. When this method is used, a sufficient number of pulses should be counted so that the time interval is long enough to average out the random fluctuations in the pulse rate of the trigger tube. Thus, by using this method, very low transmittances can be determined with the same precision as can the higher transmittances.

6.3.3 Constant Relative Errors

Relative errors are errors which are proportional to the transmittance. Thus, the relative error, $\Delta t/t$, is equal to a constant k. Equation (5.12) may then be written as

$$\Delta V/V = -k(V/b)(1/\ln\varepsilon). \tag{6.24}$$

Note that $\ln \varepsilon$ is negative. Therefore, ΔV and Δt are of the same sign.

At any given instant the relative error in the transmittance measurement is equal to the relative error in the system sensitivity and approximately equal to the sum of the relative errors in the parameters of equation (6.24). Thus, as these parameters are independent of atmospheric conditions, changes in their values are sources of constant relative errors. (Note that this is based upon the assumption that there is no significant difference between the charging current, i_c, and the photoelectric current, i.)

6.3.3.1 Projector

Tests at NAFEC, using a voltage regulating transformer, of the type currently in use in the projector power supply, showed that a change in pulse rate of about 2.4% resulted from an input voltage change of 100V to 125V. Drift in the intensity of a seasoned lamp during its service life is low, usually less than 0.5% per week, and is usually upward. The effects of the collection of dirt on the projector face is highly dependent upon the condition of the grass cover of the airfield, the proximity of jet blast, and the weather. It is, however, seldom greater than 2% per week.

6.3.3.2 Receiver

The sensitivity of the receiver is independent of the input voltage over the range 100V to 125V. The sensitivity of the pulse-amplifier unit gradually decreases in use, primarily due to decay of sensitivity in the phototube. Initial drift in phototubes has been sufficiently large so that seasoning is required. The rate of change is expected to be exponential and after 1000 hours of seasoning and service to be less than 1% per month. The change in sensitivity of a thermostatically controlled pulse-amplifier unit is of the order of 0.2% per 10°F. The effects of dirt on the receiver lens will seldom reduce the sensitivity by more than 1% per week.

6.3.3.3 Indicator

Drifts in the indicator sensitivity are not a significant factor since the indicator may be calibrated by reference to line frequency at the operator's discretion. The drift seldom exceeds 1% per day.

6.3.3.4 Illuminometer

The only effect the illuminometer has is in the selection of day and night scales. The estimated accuracy in the calibration of these instruments is 10%. An error of this magnitude will typically produce a shift in the switch over time of the order of only two minutes at 30° latitude and a shift of five minutes at 50° latitude.

6.3.3.5 System

Errors in the 100% setting resulting from errors in the estimate of visibility used to make this setting have been discussed in detail in Section 5.1.2.4. Experience indicates that the error in the 100% setting will be less than 3% with a well maintained transmissometer, with the 100% setting based upon past records, but may be much larger if the 100% setting is based upon a single estimate during a period of restricted, non-uniform visibility conditions.

6.3.4 Summary of Effects of Errors

The estimated limits of uncertainty in transmittance measurements produced by the several parameters of the transmissometer photometric system are given in table 6.3.

In order to compare the relative errors with the constant increment errors, the relative errors are converted to incremental errors by rearranging equation (6.24) so that

$$\Delta t = kt. \tag{6.25}$$

Table 6.3

Summary of Estimated Maximum Uncertainties

	Estimated* Maximum Δt
Constant increment errors due to:	
Background	
Day	+ 0.015
Night	+<0.00001
Leakage plus dark current	± 0.0005
Read-out	
Indicator	± 0.01
Converter	± 0.0003
Relative errors due to:	
Dirt on lenses	- 0.03t
Projector intensity	± 0.005t
Phototube sensitivity	- 0.002t
Temperature effect on pulse amplifier	± 0.01t
100% setting	± 0.03t

*Based upon the assumption that routine maintenance is performed weekly.

When t is near unity, the relative error in the indicated visibility can be shown to be approximately

$$\Delta V/V = \Delta t/(1-t). \tag{6.26}$$

by expanding the denominator of equation (6.12).

If $(\Delta V/V)_{max}$ is the maximum permissible relative error in the indicated visibility, the maximum transmittance, t_{max}, at which the transmissometer is useful is

$$t_{max} = 1 - \Delta t/(\Delta V/V)_{max}. \tag{6.27}$$

Since Δt is usually less than 0.03 when t is near one, after correction has been made for Δt_s, the relative error in the indicated visibility will become greater than 10% when t becomes greater than 0.70 and the day visibility becomes greater than 10 times the baseline.

Similarly, from equation (6.12) it is obvious that the minimum transmittance, t_{min}, at which the transmissometer is useful is given by

$$t_{min} = -(1/\ln t)(\Delta t/(\Delta V/V)_{max}). \tag{6.28}$$

Therefore, in this region the relative error in indicated visibility will not exceed 10% until t becomes less than about $3\Delta t$.

The over-all effect of all instrumental errors is that the errors in indicated visibility will be significant only at the extremes of visibility; clear air in which the visibility is more than 10 times the baseline, and in very dense fog, in which the visibility (by day) is less than about one-half baseline. This is clearly indicated in figure 6.11.

It should be noted that the errors tabulated in table 6.3 are maximum errors and that it is highly improbable that they would all be in the same direction. Note also that in restricted visibilities, when the transmittance is 0.1, or less, the effect of the relative errors is small in comparison with the background error. Thus by day, the background illuminance is the factor which determines the minimum transmittance at which the system will operate.

By night, the minimum transmittance, t_{min}, based upon the readout error of the converter and the leakage and dark currents is about 3 times 0.0006 or 0.002. With this transmittance, the effect of all other errors is insignificant.

In the discussion above, a tolerance of ±10% has been arbitrarily chosen for the maximum permissible error in the indicated visibility. When the transmissometer is applied to RVR measurements, the accepted tolerance is usually taken as one reportable value. Table 6.4 has been prepared to show the error in transmittance (Δt) required to produce a shift to a higher or lower reportable value for several indicated RVR's. The increments between reportable values are those given in Tables A3-11B and A3-11C, Federal Meteorological Handbook No. 1, Surface Observations (1971) [36]. They are: for 500 foot baseline instruments - 200 feet for RVR's in the range, 1,000 to 4,000 feet and 500 feet for RVR's in the range 4,000 to 6,000 feet; and for 250 foot baseline instruments - 200 feet for RVR's in the range 600 to 3,000 feet and 500 feet for RVR's in the range 3,000 to 6,000 feet. The values in the second column, t_{exact}, are the transmittance values corresponding to the RVR values listed in the first column. The column headed ΔRVR lists the changes in RVR, and the corresponding errors in transmittance Δt, required to produce a change to the next higher or lower reportable value for the RVR's listed in column 1. In calculating the transmittances, t_{exact}, corresponding to the RVR's listed in column 1, a source intensity of 10,000 candelas (step 5), a day threshold illuminance of 1,000 mile candles, and a night threshold illuminance of 2 mile candles were used.

Table 6.4

Errors in Transmittance (Δt) Required to Produce a Change in RVR (ΔRVR) Which Will Produce a Shift to the Next Reportable Value

250 Ft. Baseline

Night

RVR	t_{exact}	ΔRVR	Δt	Δt/t(%)
600	0.00470	- NA	-0.00336	71
		+ 100	+ .00658	140
1000	.0518	- 100	- .0166	32
		+ 100	+ .0190	37
2000	.271	- 100	- .0214	7.9
		+ 100	+ .0207	7.7
3000	.448	- 100	- .0148	3.3
		+ 250	+ .0345	7.7
4000	.567	- 250	- .0257	4.5
		+ 250	+ .0234	4.1

Day

RVR	t_{exact}	ΔRVR	Δt	Δt/t(%)
600	0.0626	- NA	-0.0326	52
		+ 100	+ .0412	66
1000	.245	- 100	- .0473	19
		+ 100	+ .0457	19
2000	.588	- 100	- .0239	4.1
		+ 100	+ .0221	3.8
3000	.751	- 100	- .0117	1.6
		+ 250	+ .0262	3.5
4000	.836	- 250	- .0170	2.0
		+ 250	+ .0149	1.8

Table 6.4 (Continued)

500 Ft. Baseline

Night

RVR	t_{exact}	ΔRVR	Δt	Δt/t(%)
1000	0.00268	- NA	-0.00145	54
		+ 100	+ .00232	87
2000	.0732	- 100	- .0111	15
		+ 100	+ .0117	16
3000	.200	- 100	- .0130	6.5
		+ 100	+ .0129	6.4
4000	.322	- 100	- .0112	3.5
		+ 250	+ .0271	8.4

Day

RVR	t_{exact}	ΔRVR	Δt	Δt/t(%)
1000	0.0599	- NA	-0.0209	35
		+ 100	+ .0245	41
2000	.346	- 100	- .0275	7.9
		+ 100	+ .0265	7.7
3000	.564	- 100	- .0175	3.1
		+ 100	+ .0166	2.9
4000	.700	- 100	- .0109	1.6
		+ 250	+ .0251	3.6

6.4 CONSIDERATIONS OTHER THAN INSTRUMENTAL ERRORS

6.4.1 Scattered Light Errors

In a fog, a telephotometer such as the transmissometer receiver will receive, in addition to the light which passes directly from the source to the receiver, some light which, though radiated by the source, would not reach the receiver in clear weather. This scattered light constitutes an error in the transmittance measurement as shown in Section 5.1.3. Under conditions of dense fogs this error may become large. The error is minimized by keeping the field of view of the receiver and the beam spread of the projector small. Measurements made at Arcata indicate that when the field of view of the receiver and the beam spread of the projector are no larger than those in the NBS transmissometer, these errors do not cause a significant error in the indicated visibility under present operating conditions as shown in table 6.5.

Table 6.5

Average Scattered Light Errors

for a 500 foot Baseline Transmissometer

"True" Transmittance	Percent Error in Transmittance	Percent Error in Day Visibility
0.5	0.8	1.2
.1	4.6	2.0
.01	12	2.5
.001	24	3.2
.0001	47	4.4

Note the very small error in day visibility corresponding to the rather large scattered light error in the transmittance measurements at low transmittances. Errors in the visual range of lights would be slightly less.

Although the scattered light error is not significant for the fog densities under which the tests were conducted, it will become significant at very high fog densities. The effect of the scattered-light error on the indicated visual range is independent of the transmissometer baseline for a given transmissivity although the scattered light error for a short baseline instrument will be lower because of the higher transmittance over the short baseline [108].

6.4.2 Sampling Errors

The foregoing analysis is based upon the performance of the transmissometer alone. No consideration has been given to the variation in transmittance in time and location nor to whether the sample measured by the transmissometer is representative of the atmosphere in general. Experience indicates that, in general, the "sampling error" is the limiting factor and that the differences between indicated and observed visibilities resulting from sampling differences are larger, and often much larger, than those resulting from instrumental errors. The extent of variations in transmittance with time and place is illustrated in the following examples of transmissometer records. These records were obtained by NBS from transmissometers located at Arcata, California. The fogs there are predominantly advection fogs. The locations of some of the instruments on the field are shown in figure 6.12. Figure 6.13 is an aerial view of the field showing the terrain around the visibility test area.

Figures 6.14, 6.15 and 6.16 are examples of simultaneous chart records obtained with 250 foot baseline transmissometers T-L1, T-L2, and T-L3. Time is shown along the bottom of the charts, running from right to left, and the transmittance over the transmissometer baseline is shown across the chart with each major division representing an increment in transmittance of 0.10. Runway visual ranges, based upon intensity step 5 day operation, as a function of the transmittance over a 250 foot baseline are given in table 6.6 as an aid in studying the significance of temporal and spatial variations in transmittance.

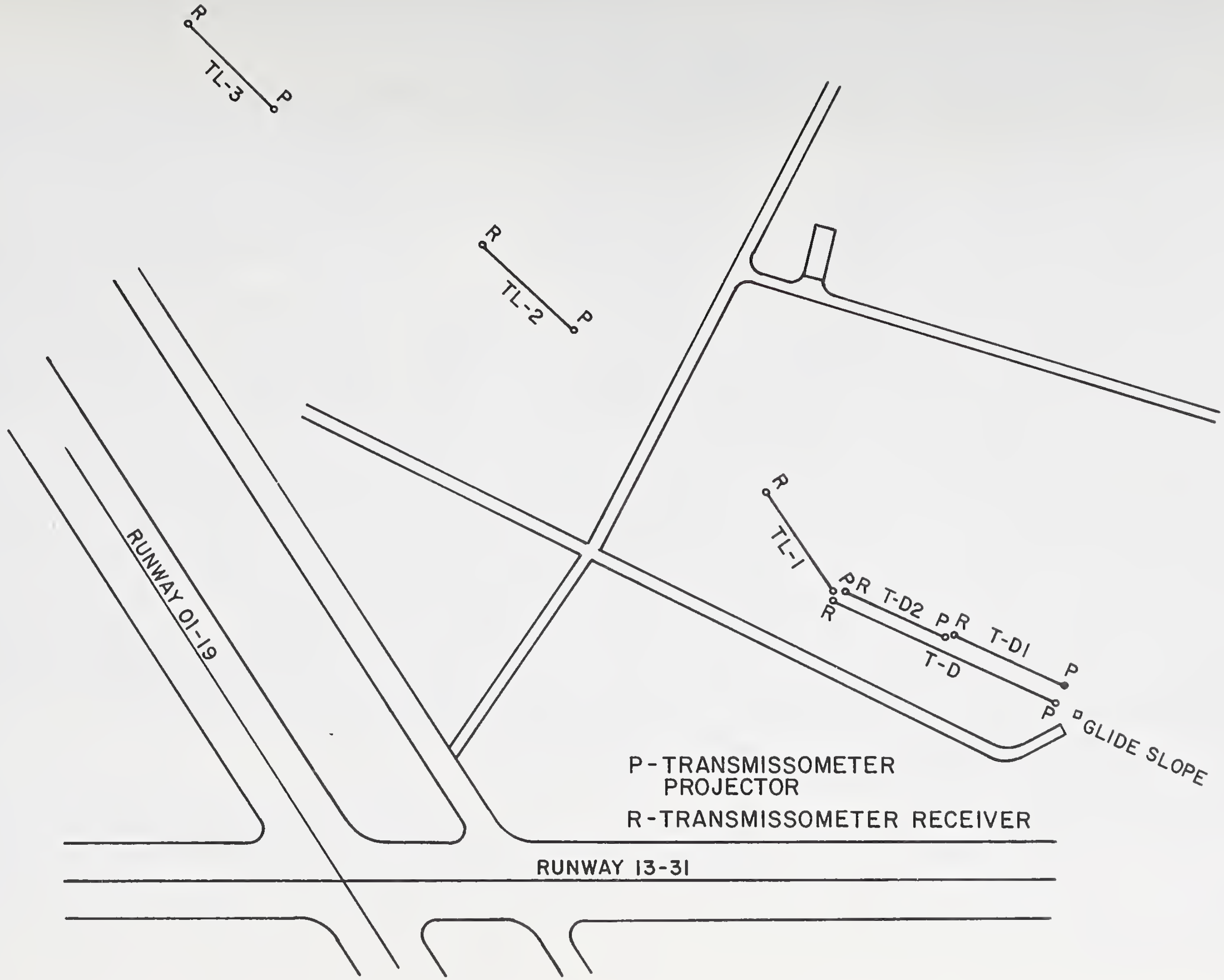

Figure 6.12 Locations of some of the transmissometers at Arcata, California.

Figure 6.13 Aerial view of Arcata, California, airport showing the transmissometer test site. Transmissometers are located to the right of runway 31.

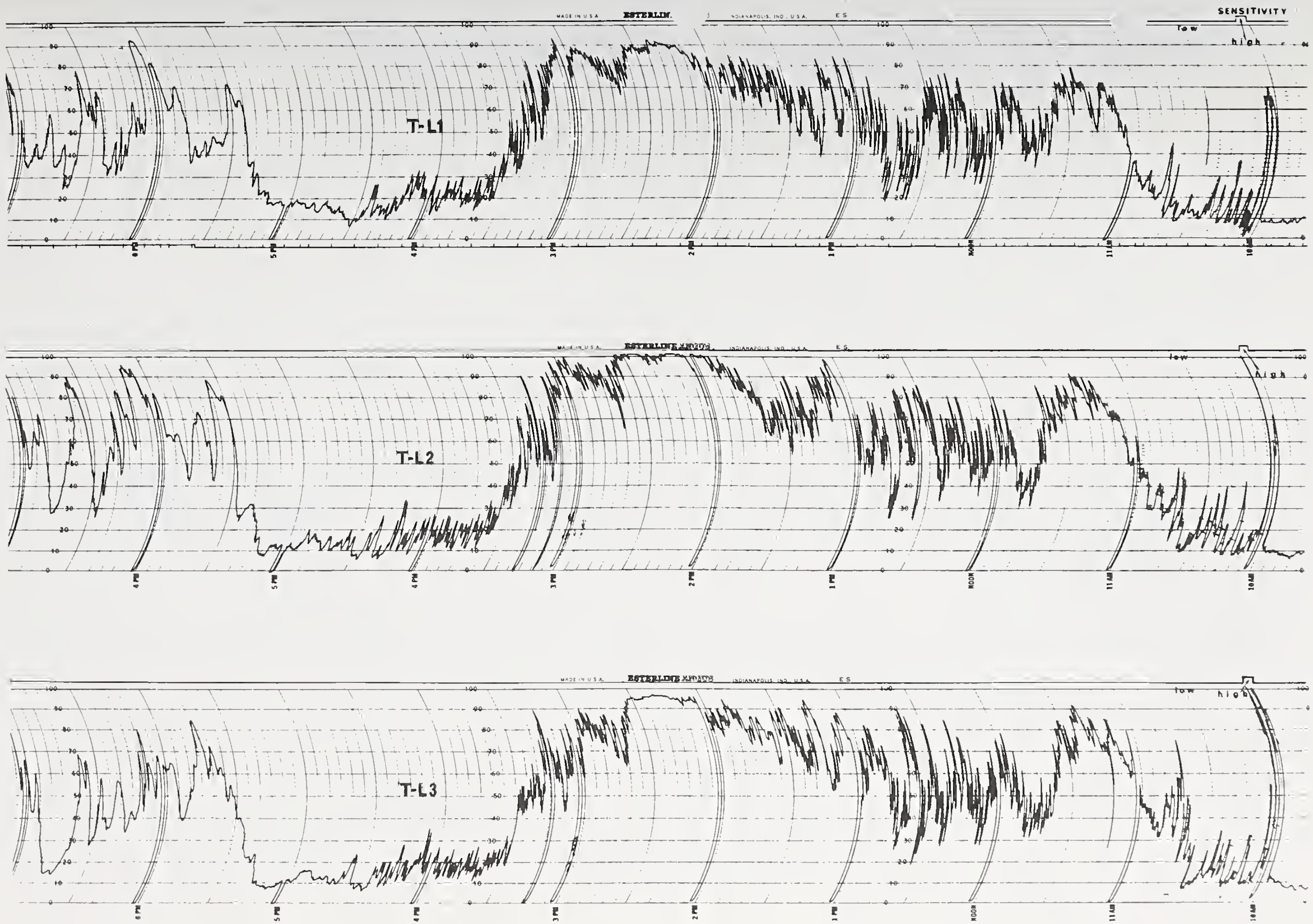

Figure 6.14 Fog of October 24, 1966, an example of rapid variations in fog density with time.

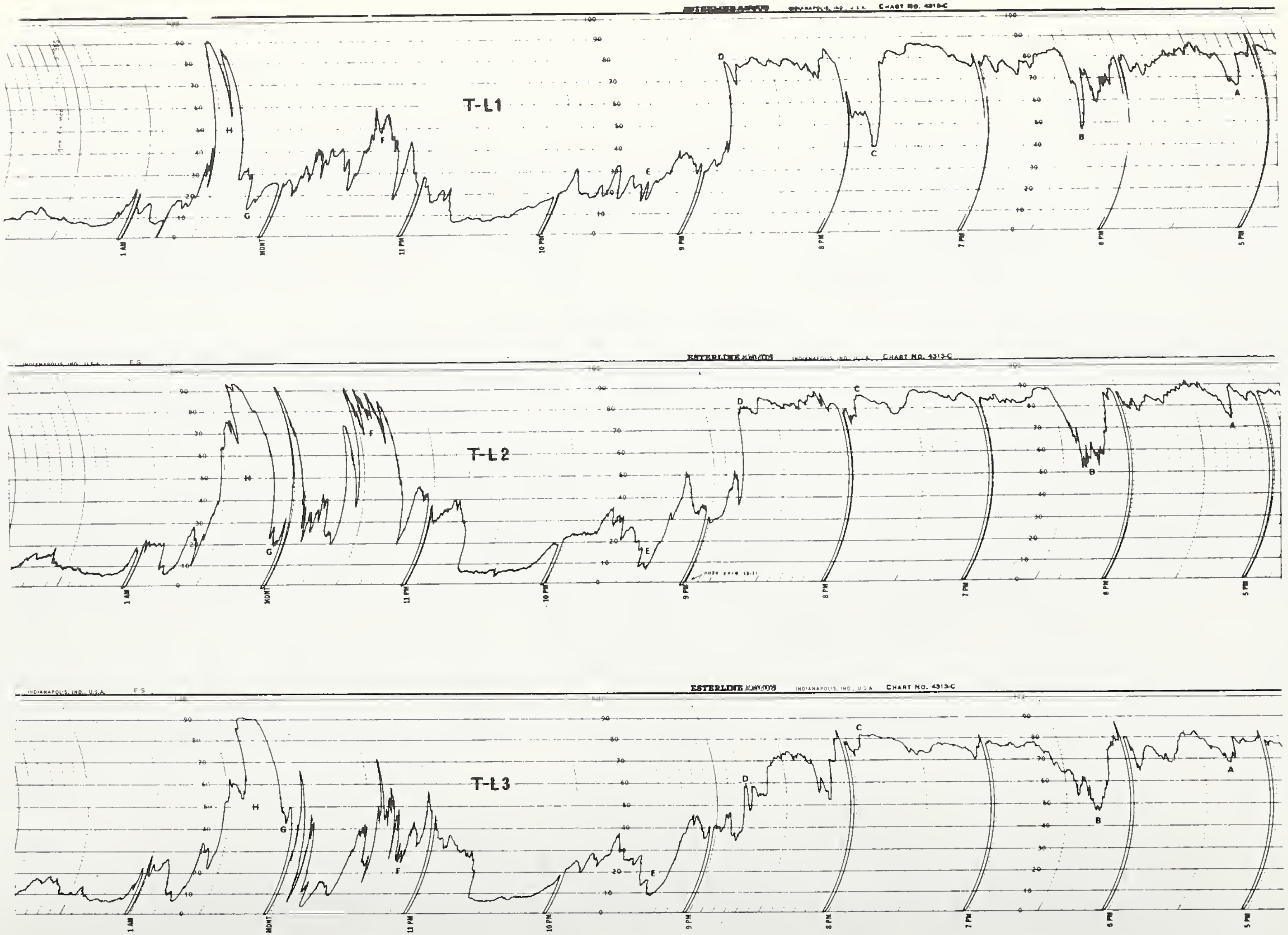

Figure 6.15 Fog of October 22-23, 1966, an example of records showing variations in fog density at the locations of the transmissometers. (The letters identify points of pronounced differences.)

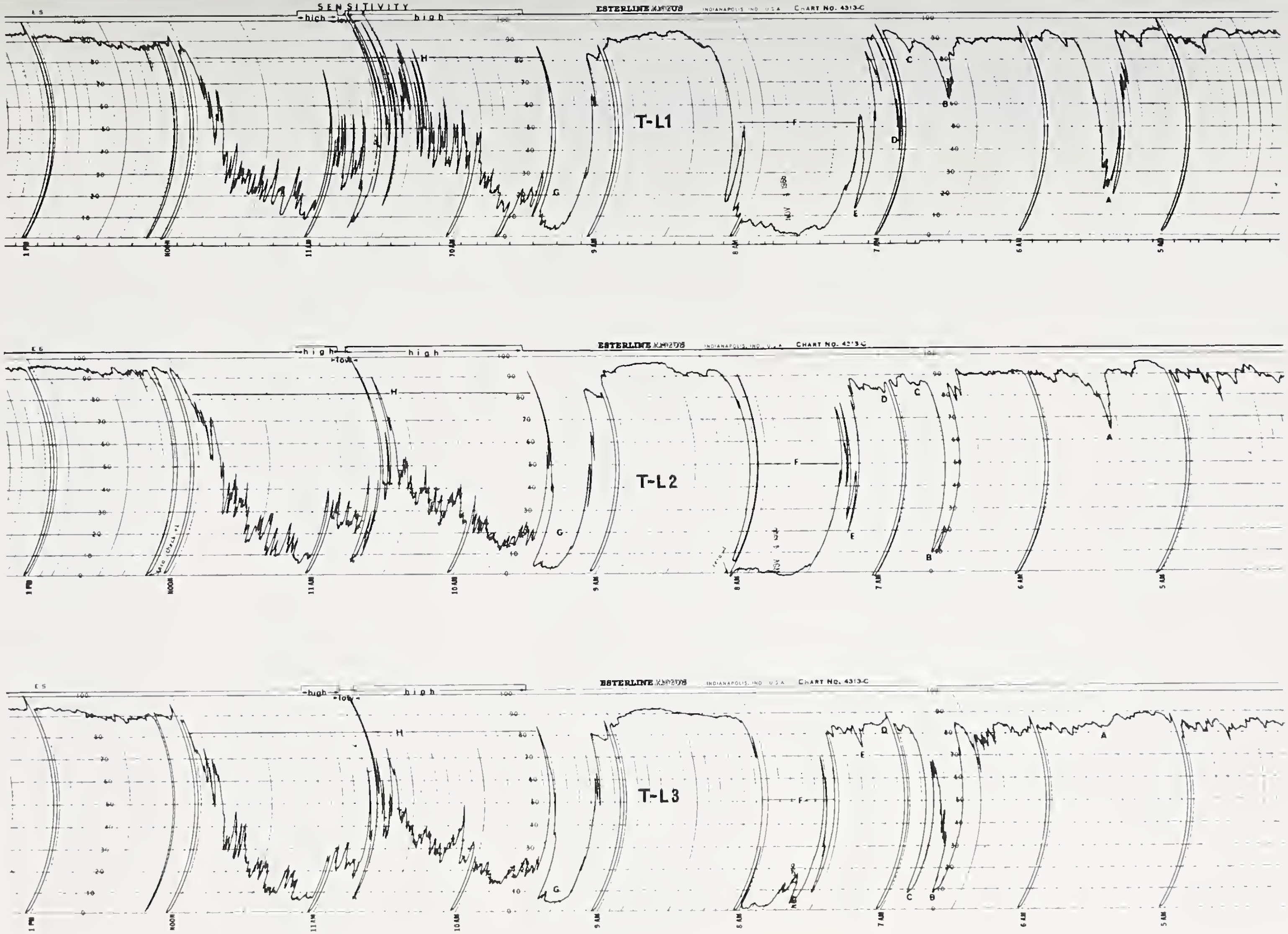

Figure 6.16 Fog of November 4, 1966, an example showing variations in fog density at the locations of the transmissometers and also rapid changes with time. (The letters identify points of interest.)

Table 6.6

Relation between Transmittance over a 250 foot Baseline and RVR (Step 5, Day)

t_{250}	RVR (feet)
0.02	500
.05	550
.10	700
.20	900
.30	1100
.40	1400
.50	1700
.60	2000
.70	2600
.80	3500

Simultaneous measurements were also made at Arcata with two end-to-end 250 foot baseline transmissometers (TD-1 and TD-2) located near the touchdown zone of runway 31, as shown in figure 6.12.

The records of these two instruments during a five hour fog are shown in figure 6.17. For ease in comparison the records of the two instruments have been placed on a single chart. In obtaining these records, the transmissometer recorders were operated with a chart speed of 12 inches per hour, instead of the usual speed of three inches per hour. Again time runs from right to left.

Runway visual ranges have been computed from these transmittance records using, for convenience, a 75-second integrating period. The results of these computations are given in figure 6.18. A comparison of figures 6.17 and 6.18 demonstrates the value of a suitable integrating period.

An example of a record of a fog of extreme variability obtained with a 500 foot baseline transmissometer installed in the touchdown zone is shown in figure 6.19. Such fogs are not rare at Arcata.

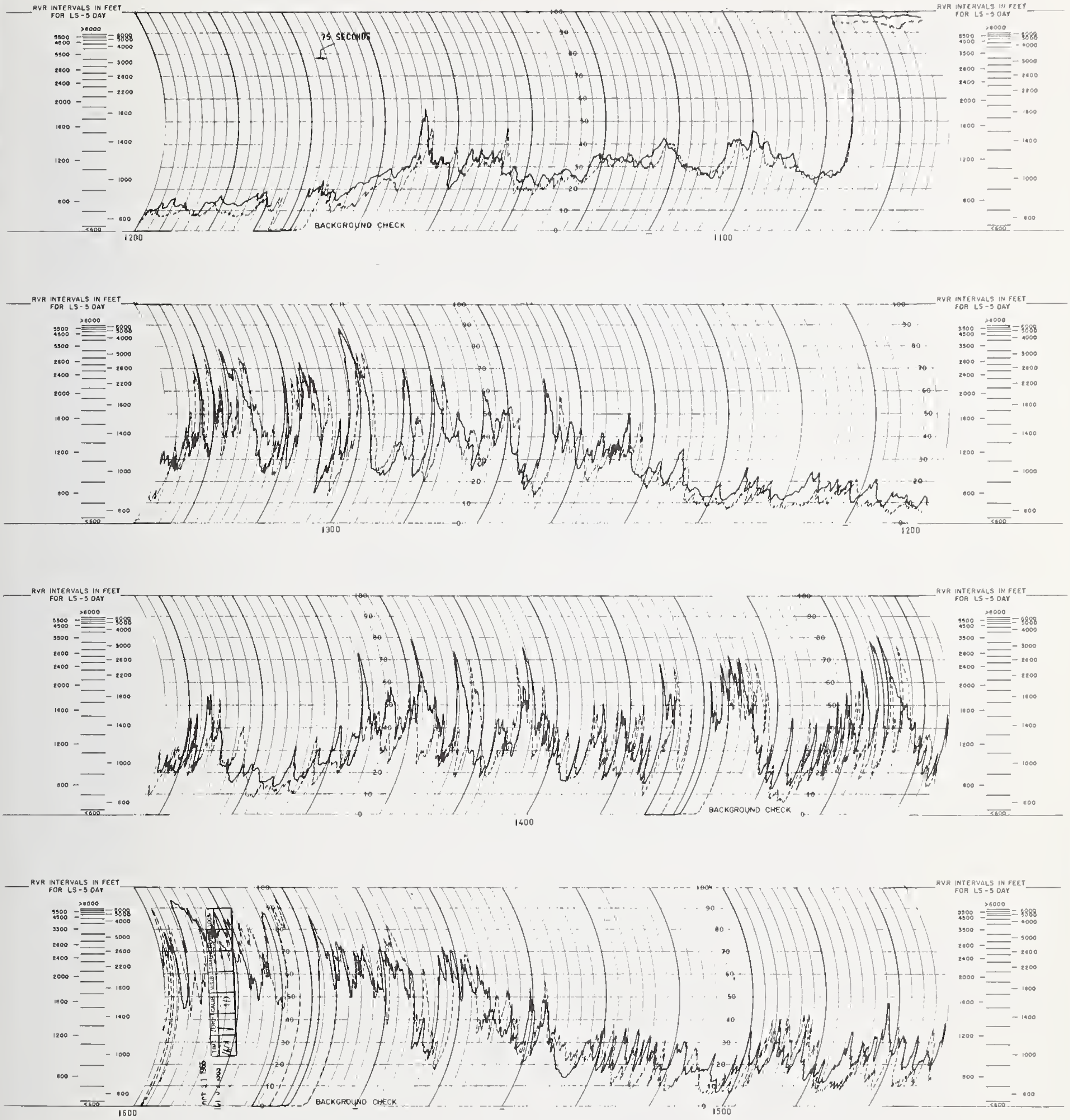

Figure 6.17 Simultaneous records of two back-to-back, 250 foot baseline transmissometers at Arcata, California, October 31, 1965. The solid line corresponds to transmissometer TD-1 and the dashed line to TD-2 as shown on figure 6.12. Times, which run from right to left, are shown at the bottom of charts, RVR scales for LS-5 day at each end. Distance between parallel "vertical" arcs on chart represents 75 seconds.

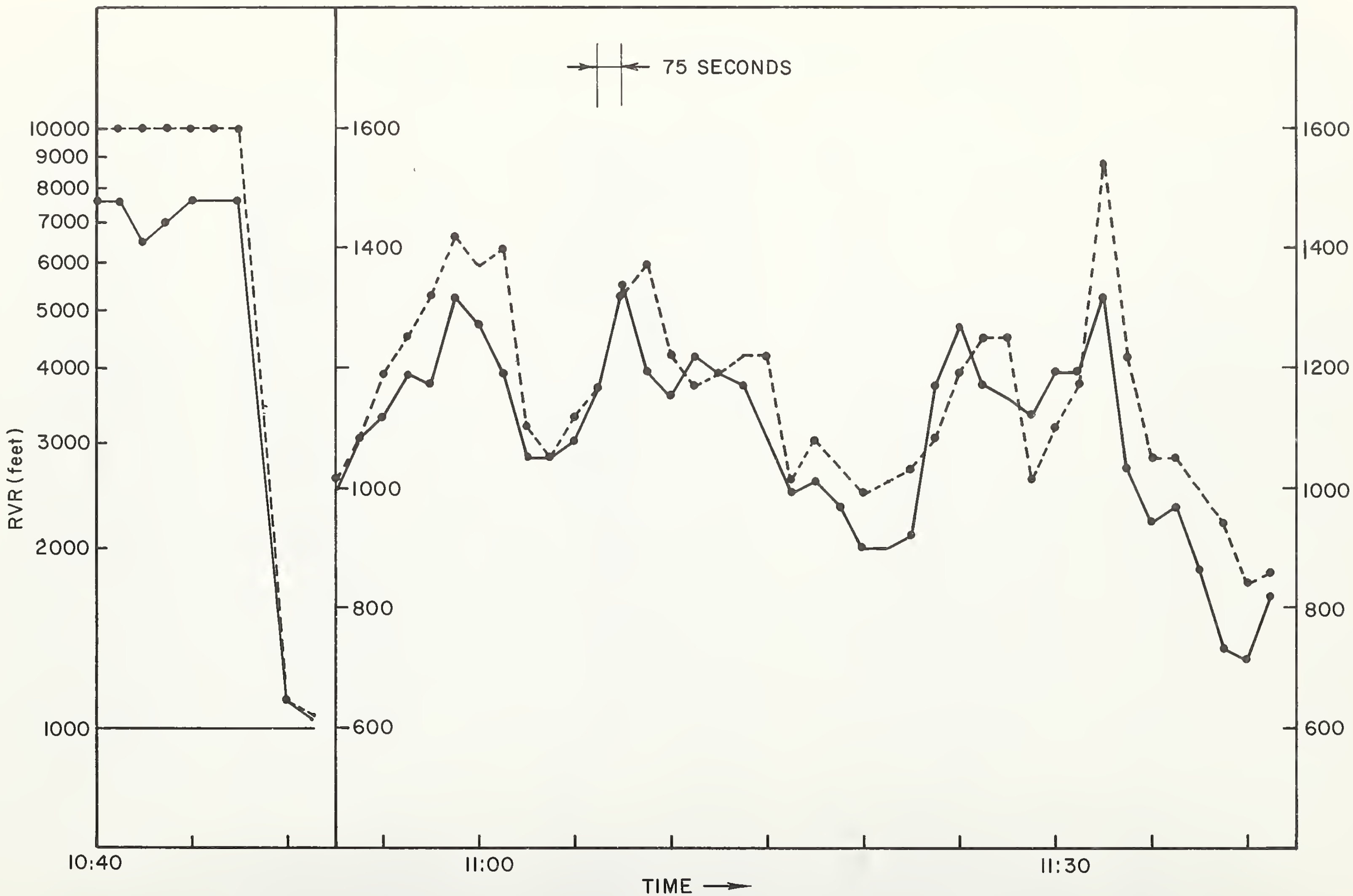

Figure 6.18 Simultaneous RVR determinations from two back-to-back transmissometers at Arcata, California, October 31, 1965. RVR is based on the step 5, day scale. The integrating period was 75 seconds. Note that RVRs plotted above 4000 feet are based on the visual range of lights, whereas, in practice, RVRs above 4000 feet are based on object visibility.

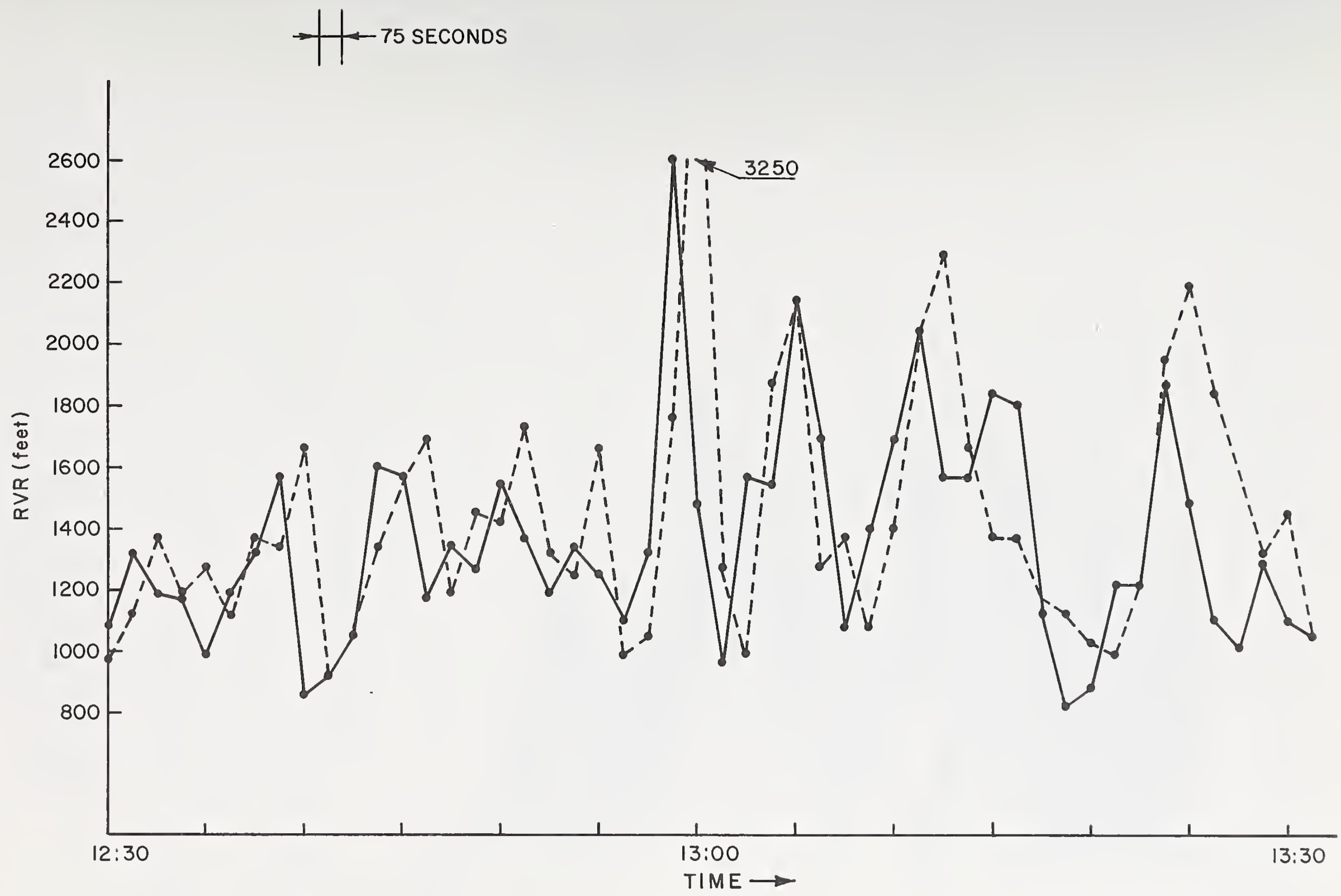

Figure 6.18 (Continued) (Note change in RVR scale.)

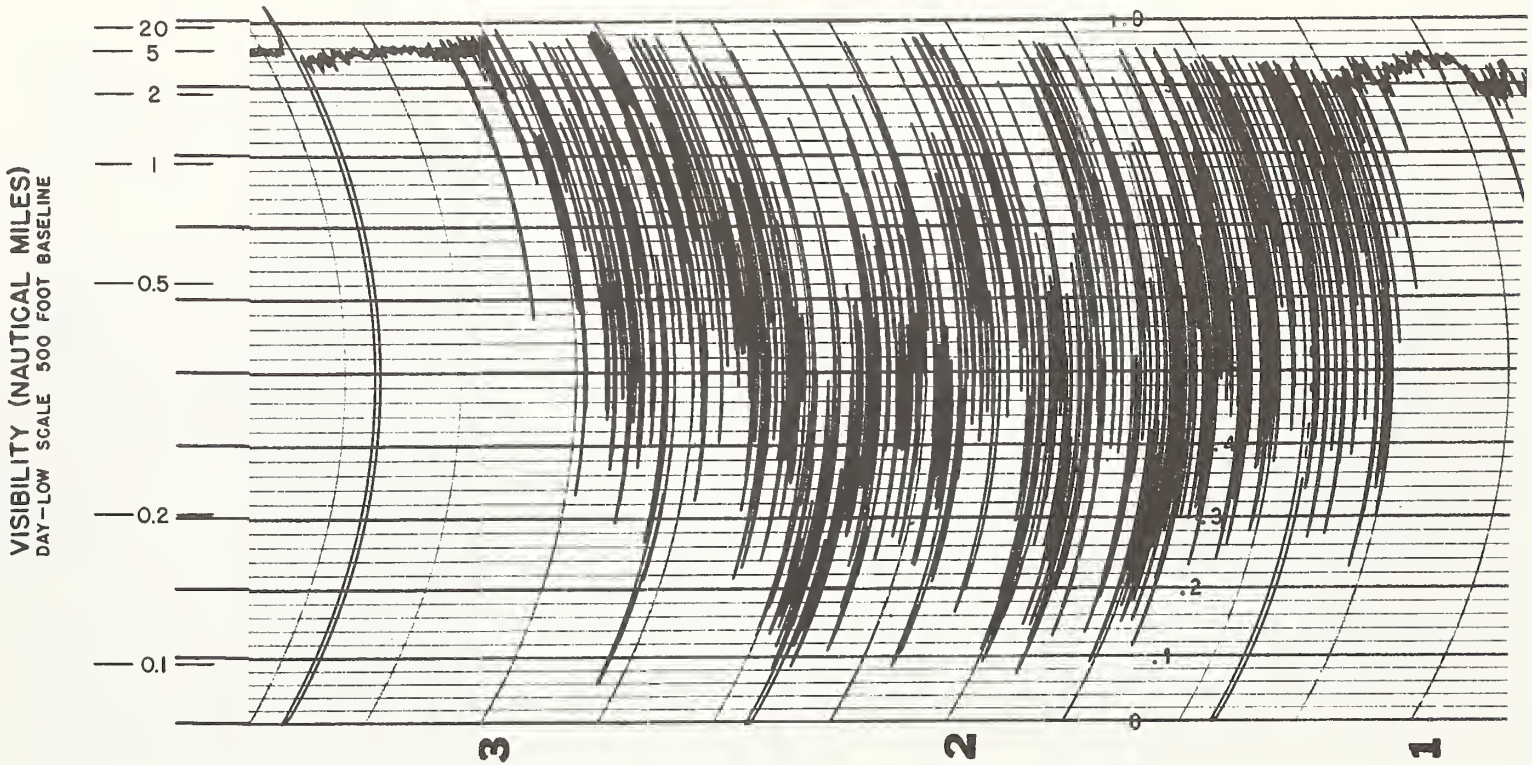

Figure 6.19 An example of extreme variations of transmittance with time. Record was obtained from a 500 foot baseline transmissometer at Arcata. Numbers along bottom of chart indicate time (PM) in hours.

6.4.3 Spectral Sensitivity of Phototubes

Note that the pulse amplifier contains no filter to modify the spectral response of the phototube. This apparent omission has caused concern to some, for example Middleton [95]. At first thought, it would appear that such a filter should be provided so that the phototube-filter combination has a spectral response similar to that of the eye, that is, the CIE standard observer luminous efficiency function. However, it should be noted that if the transmissivity of the atmosphere does not change with wavelength throughout the waveband in which the eye and the transmissometer receiver respond, the spectral sensitivity of the transmissometer is immaterial. Moreover, when Koschmieder's and Allard's laws, in their usual form, are applied to situations where the visual range differs significantly from the length of the transmissometer baseline, an atmosphere which is nonselective is tacitly assumed. Otherwise Allard's law would take the form

$$E = \int_{380}^{760} P_\lambda \, V_\lambda \left(T_\lambda\right)^x \, d\lambda/x^2, \tag{6.29}$$

or

$$E = \int_{380}^{760} P_\lambda \, V_\lambda \left(t_{b,\lambda}\right)^{x/b} \, d_\lambda/x^2 \, . \tag{6.29b}$$

where

- P_λ is the spectral intensity, at wavelength λ, of the source being viewed,
- V_λ is the spectral sensitivity of the eye at wavelength λ,
- T_λ is the transmissivity at wavelength λ,
- $t_{b,\lambda}$ is the transmittance over the baseline b at wavelength λ, and
- x is the distance between the observer and the light.

Similarly Koschmieder's law would take the form

$$C = \int_{380}^{760} C_{o,\lambda} \left(T_\lambda\right)^x d\lambda, \tag{6.30a}$$

or

$$C = \int_{380}^{760} C_{o,\lambda} \left(t_{b,\lambda}\right)^{x/b} d\lambda \tag{6.30b}$$

where

$C_{o,\lambda}$ is the contrast between the object and its sky background at wavelength λ.

Moreover, an instrument which uses a single measurement of the entire visible spectrum is not suitable. Instead this transmittance must be obtained from measurements of the spectral transmittance, wavelength by wavelength, to obtain $t_{b,\lambda}$ over the spectral region 380 to 760 nanometers.

Note: Current recommended practice is to denote wavelength λ in parentheses when the quantity is a function of wavelength, e.g., $V(\lambda)$, and to use a subscript λ to denote spectral concentration of a quantity to a narrow wavelength band, e.g., P_λ. However, in the interest of clarity in equations, subscripts of λ have been used for both types of quantities in this document.

As stated by Zuev in his comprehensive review of atmosphere transparency [129], the transmissivity of all fogs, clouds, and rain is virtually independent of wavelength in the visible spectrum (this accounts for the white color of clouds). However, Zuev also shows that in haze the transmissivity for red light is greater than for blue, but that the difference decreases as the haze density decreases.

Since haze atmospheres are somewhat selective, it is appropriate to re-examine the spectral sensitivity of the transmissometer receiver. As mentioned, correction of the detector's spectral response to duplicate that of the human eye would initially seem to be both desirable and necessary. Consider, however, an extreme case of atmospheric sensitivity. Suppose that, in dense fogs, blue light at wavelengths shorter than 480 nm was totally attenuated but wavelengths above 480 nm were attenuated only slightly. In this hypothetical situation, a transmissometer system with a receiver corrected to the spectral sensitivity of the eye and with an incandescent lamp, or other sources which are not predominantly blue, as the light source would indicate an RVR far in excess of the visual range of blue lights. From this example we can see that correction of only the receiver's response is not sufficient and that consideration must also be given to the spectral power distribution of the transmissometer light source and to the signalling light or object to be viewed as well as to the spectral sensitivity of the eye and of the transmissometer receiver. The most desirable situation would be to make the product of the spectral sensitivity of the transmissometer receiver and the spectral power distribution of the transmissometer source proportional to the product of the spectral sensitivity of the eye and the spectral power distribution of the light or object being viewed, that is

$$\int_{380}^{760} M_\lambda \; S_\lambda \; d_\lambda = k \int_{380}^{760} V_\lambda \; P_\lambda \; d\lambda \qquad (6.31)$$

where

- M_λ is the spectral power distribution of the transmissometer source,
- S_λ is the spectral sensitivity of the transmissometer receiver,
- V_λ is the spectral sensitivity of the eye,
- P_λ is the spectral power distribution of the the light or object being viewed, and
- k is a proportionality constant.

Thus, a filter which modifies the spectral sensitivity of the receiver to that of the eye, as proposed by some, would be suitable when undimmed white lights are the visual signal but would not be suitable if sources with different spectral distributions (such as xenon flashers, red approach lights, green threshold lights, blue taxiway lights or runway markings) are the visual signal since the transmissometer light source is a clear incandescent light.

The receiver of the NBS transmissometer uses a phototube with a type S-1 (red-sensitive) cathode. The double-peaked spectral sensitivity curve of this tube does not approximate that of the eye. However, its response range of 300-1080 nm encompasses that of the human eye.

The phototube used in the early receivers (figure 6.1) had an S-4 (blue-sensitive) cathode which is a better, although poor, approximation of the eye's response. However, these tubes had undesirably high dark and leakage currents and were not sufficiently stable. They were, therefore, replaced with the type 919, or C-75, tubes with an S-1 surface. Use of a correcting filter is not feasible with these latter tubes because of the extreme loss in sensitivity which would be incurred. Over the years all efforts to obtain phototubes with a more appropriate spectral sensitivity have been futile.

In considering the need for a tube with improved response, it should be noted that transmissometers having S-1 phototubes, have been operated simultaneously at Arcata with transmissometers having S-4 phototubes, thereby bracketing the spectral sensitivity desired. No systematic differences were detected. Presumably, such differences as exist were concealed by variations in fog density with time and location.

7. PERFORMANCE VALIDATION OF THE NBS TRANSMISSOMETER

7.1 INTRODUCTION

In 1945, Douglas and Young reported on the development of a transmissometer for measuring visual range [30]. The principles of operation of this instrument and a discussion of errors are contained in Chapter 5 of this report, and its development and application are discussed in Chapter 6. This chapter is a discussion of the performance validation of the instrument with particular emphasis on the field experiments conducted by NBS on Nantucket Island and at Arcata and those sponsored by the Air Navigation Development Board (ANDB) at Washington National Airport [124]. The general purpose of all of these field experiments was to determine the correlation between the visual range of selected objects and lights, as determined by human observers, and the transmittance measurements obtained with the transmissometer. Both Koschmieder's and Allard's laws (see Sections 4.1.2 and 4.3.1) involve threshold constants which must be used in determining visual range from transmittance data. Values for the contrast threshold and the illuminance threshold were determined from data obtained during these field experiments. The actual procedures and techniques employed during these experiments are described in a fair amount of detail to enable direct comparisons with any future work in the determination of threshold calibrations. As a result of these studies, it has been shown that the correlation between the transmittance measurements and the visual range of non-luminous objects by day follows the theory developed by Koschmeider, whereas that between transmittance measurements and the visual range of lights at night shows systematic deviations from Allard's Law.

7.2 DESCRIPTION OF FIELD EXPERIMENTS

7.2.1 Nantucket Island

The NBS transmissometer was field tested and its performance initially validated on Nantucket Island, Mass., during the summer of 1941. Since this location had already been chosen for fog observations in the development of approach light systems, it was an obvious choice for the transmissometer performance validation because personnel and equipment could be applied to both projects. The equipment was installed about one-quarter mile from the south shore of the island near Surfside where periods of fog were frequent. An aerial photograph of the locality is shown in figure 7.1.

The light source and the receiver were mounted on 3 inch pipes set about 2 feet into the ground and rigidly guyed by wires. The units were located about 6 feet above the surface of the ground. The output meter was installed in the control house located about 175 feet from the receiver. Diaphragms with 10 inch holes were installed in front of the light source at distances of 12 and 50 feet to restrict the cross-section of the beam because the projector used gave a broader beam than that considered desirable for service use.

The row of daytime visibility marks shown in figure 3.2 consisted of ten 4-foot-square pieces of plywood painted flat-black and spaced at 100 foot intervals. The lower edges were about 8 feet above the surface of the ground so that the marks would be observed against a background of fog rather than against the terrain. The line of the marks was parallel to and approximately 250 feet from the light path of the transmissometer.

A light was mounted on top of each of the visibility marks for observations at night. These lights consisted of clear-bulb street-series lamps and were operated at an intensity of 25 candelas. The variation of the intensity of the lamps with horizontal angle was negligible.

Figure 7.1 Location of visibility calibration range on Nantucket Island.

Observation stations were laid off at 100 foot intervals throughout the length of the observation area. Telephone terminals were provided at each of the observation stations.

Because of the flat terrain and lack of a sufficient number of suitable marks and lights, it was necessary to provide a mark and light which could be observed for distances between 1000 and 3500 meters. Figure 3.2 also shows this visibility mark which consisted of two 4 foot by 8 foot pieces of plywood painted flat-black and mounted about 100 feet from the control house. A 25-candela light and a signalling lamp were outside the areas shown in figure 7.1. The distances to these various stations were approximately 1000, 1300, 1500, 1800, 2400, and 3500 meters respectively. The distances were established by surveying. The stations were located, as nearly as possible, the same distance from the shore line as the mark and in a direction approximately normal to the plane of the mark.

7.2.1.1 Visibility Calibration Procedure

The visibility marks and lights were observed from the observation area indicated in figure 7.1 for visual ranges less than 1000 meters. The observer would locate himself, if possible, at that observation station from which approximately only one half of the visibility marks or lights were visible. Then, every minute, he would report by telephone to an associate in the control house the number of marks or lights that could be seen. The visual range was considered to be the distance to the last mark or light which could be seen steadily. The associate would list this visual range information, together with the transmissometer reading taken at approximately the same time. When the visual range changed so no marks or lights were visible or all were visible, the observer, if possible, would proceed to another station from which about half of the marks or lights could again be seen and the observations continued. For twilight conditions, observations were made on both the marks and the lights.

When the visual range of the marks or lights was greater than 1000 meters, recourse was made to the large mark or its associated light. The observer would go to the station from which the mark appeared to be approximately at the limit of visibility and would record the periods, if any occurred, during which this mark was at the limit of visibility. When the visibility of the mark changed sufficiently so the observer believed that the mark might be at the limit of visibility from some other station, he would proceed to that station so that he could again determine the periods during which the mark was at the limit of visibility. Throughout the period of these observations the associate would list the transmissometer readings at intervals of 1 minute. When this type of observation was made at night the signal light of about 75 candelas intensity was flashed from time to time to identify the visibility light.

In addition to the observations on the large mark or associated lamp, the appearance of other objects and lights at known locations, which were at the limit of visibility for either the observer or the recorder, was listed. For visual ranges somewhat greater than 3500 meters, natural objects such as church steeples, water towers, and lights of the villages of Nantucket and Siasconset located on the island were observed.

During the periods of daytime observations the light source of the transmissometer was turned off from time to time to determine the transmissometer reading due to background illuminance. In the reduction of the data the background reading was subtracted from the reading with the light on to obtain the true transmittance reading. Also, transmissometer readings were obtained from time to time when the atmosphere was especially clear. These values were used in estimating the transmissometer reading for 100 percent transmittance.

Since the visual range data were to be used primarily to calibrate the transmissometer, the calibration observations were not made during periods when the fog or haze was obviously non-homogeneous or when the visual range was fluctuating rapidly.

In addition to the above observations, the transmissometer reading was frequently recorded at the time during which the Nantucket Weather Bureau Station, about 2-1/2 miles away, made its periodic observations.

7.2.2 Arcata

Comparative visual range observations were made by NBS at Arcata during the 1947, 1948, and 1954 fog seasons.

The 1947 observations by day used a single fixed target while varying the position of the observer. Subsequent observations in 1948 used a path of sight which nearly duplicated that of the transmissometer.

The 1947 observations by night attempted to investigate the effects of unseen lamp glow upon the illuminance threshold. Comparative observations were made in 1954 of two lamps, one shielded and one unshielded, to further investigate the effects of lamp glow.

7.2.3 Washington National Airport

In the early 1950's, the Weather Bureau, at the request of the Air Navigation Development Board, conducted a series of investigations at Washington National Airport. The objectives were two-fold:

a) to independently validate the performance of the NBS transmissometer in the field and

b) to compare the prevailing visibility reported by a stationary observer at the end of the runway with the visual range determined through the use of a nearby transmissometer.

Comparisons were made between a transmissometer located near the touchdown point on runway 36 at Washington National Airport and the visibility reported by an observer stationed at the end of the runway. Figure 3.12 shows the airport and the location of the various instrumental and observational sites.

7.2.3.1 Validation Procedures

A mobile observatory was constructed to house the observer and some of the instruments necessary for taking observations at the end of the runway. The indicator for the transmissometer was installed in the main observatory, so that all visual observations made by the runway observer were without reference to instrumental indications.

Targets used to determine daytime visibility were ordinary buildings, trees, etc., but were selected with as much care as possible, consistent with the need for obtaining a sufficient number for the purpose. Although it was impossible to do so completely, an attempt was made to select dark objects against a horizon sky background and to select those having one dimension which subtended an angle to the observer's eye of not less than 1/2 degree and not more than 5 degrees. Point-source lights were selected for night targets. Red and white lights with effective intensity of from 25 to 75 candelas predominated. Focused lights were not used. These criteria reduced the number of available targets less than three miles away to 29 for daytime and to 21 for nighttime. In any quadrant there were only 5 or 6 targets within the three mile range, resulting in very few observations being made when a target was exactly at the observer's visual range. In order to provide as much precision as possible under these circumstances, a target clarity code was devised whereby the runway observer would grade the clarity with which any visible target was observed. Five code numbers were used, with the following definitions:

1. Target barely detectable: appears to fade in and out, visible not more than 75% of the time.
2. Detection threshold: target appears to fade in and out but is visible more than 75% of the time.
3. Recognition threshold: target in view 100% of the time and is defined just clearly enough to be recognized.
4. Just better than recognition threshold: good definition with some texture and color realized in daytime targets.

5. Prominent: sharp outline, details stand out, colors of close targets recognized.

In addition to estimating the quadrantal visibility, in standard visibility increments, the runway observer noted the targets used and the clarity with which they were observed, expressing results on the basis of the above code. In accordance with standard meteorological practice, visibility was determined by using the so-called "recognition threshold" [73].

During the latter portion of the program measurements of background luminance were made during periods of twilight and darkness.

7.3 DISCUSSION OF RESULTS - DAYTIME OBSERVATIONS

7.3.1 Nantucket Island

Between two and three thousand simultaneous observations of the visual range and transmissometer reading were made. Approximately one third of these data were rejected as unsuitable for determining the visibility calibration curves. The data were rejected because the transmissometer reading of visual range did not remain sufficiently constant to give a reliable calibration point. For the acceptable data, the average values of the transmissometer readings and of the visual ranges during each period when both remained reasonably constant were used to determine a calibration point. The points were graded in accordance with their relative reliability, using as a measure of reliability the constancy of the transmissometer readings and visual-range observations and the length of the period of constancy.

Grade A points were obtained in general from periods of 10 to 30 minutes or more duration during which the transmissometer readings and visual range varied relatively little. As an illustration, the individual values from which one of the better grade A points was obtained are listed in table 7.1.

Grade B points were obtained in general from periods 5 to 10 minutes in length and occasionally with slightly more variation in the data than for grade A points.

Grade C points were obtained primarily from two types of data, (1) periods of less than 5 minutes in duration, and (2) single visual-range observations with reasonably steady atmospheric conditions as indicated by the transmissometer readings.

The grade A, B, and C points include only the visual range observations made on the special marks and lights installed for the calibration. The calibration points obtained from observations on other objects and lights and from the Nantucket Weather Bureau observations have not been graded. Weather Bureau data listing prevailing visibilities less than the distance (2.5 miles) from the station to the test location were not used for calibration points.

Figure 7.2 is a plot of the daytime visibility calibration points for observations made on marks. The visual range is plotted on a log scale and the transmittance on a log-log scale. With these scales Koschmieder's law (4.08) is represented by a family of straight lines having a slope of one, with the contrast threshold, ε, as a parameter.

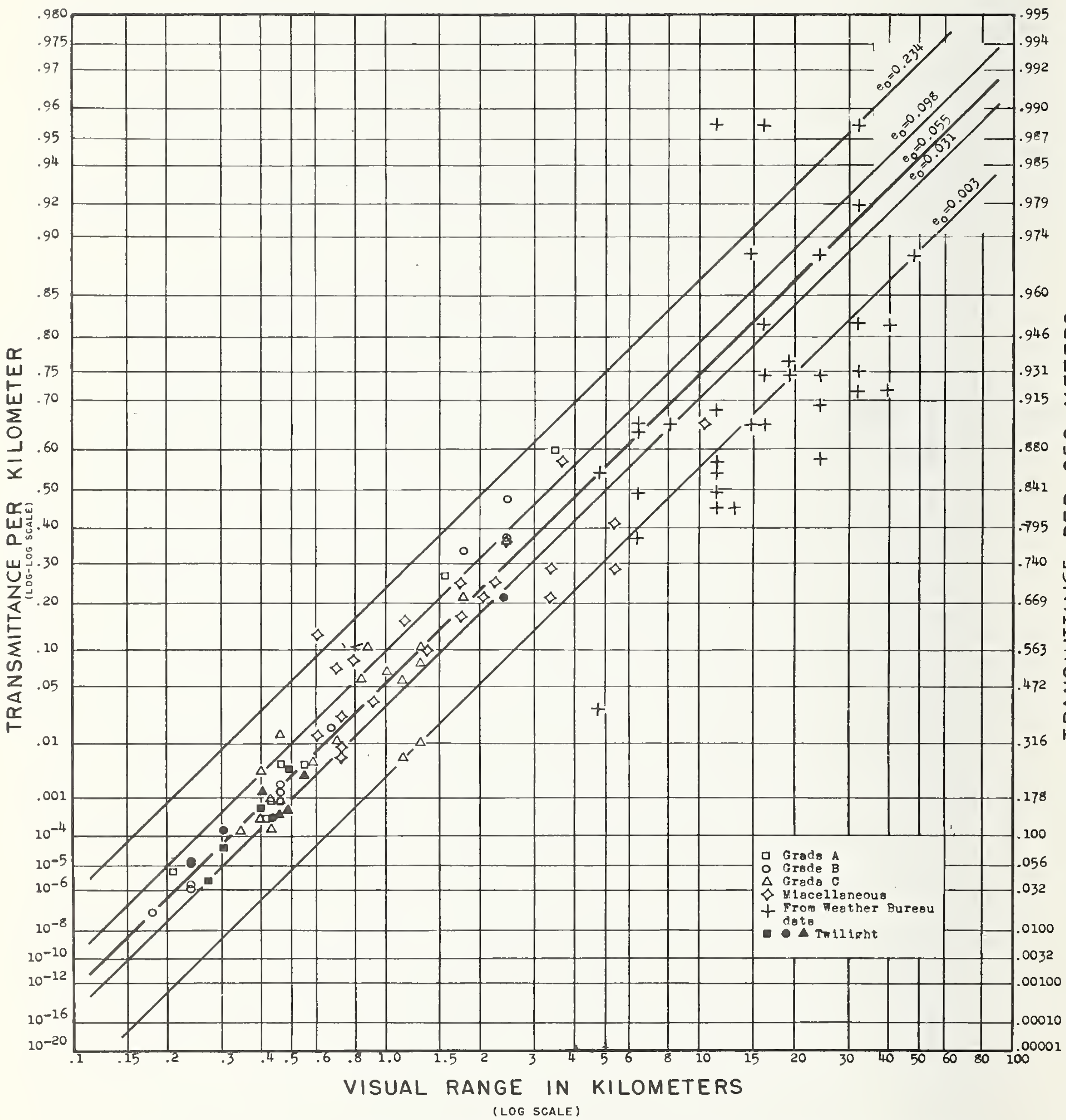

Figure 7.2 Daytime transmissometer visibility calibration curve derived from data obtained at Nantucket Island. [30]

TABLE 7.1

DATA USED TO DETERMINE ONE OF THE GRADE A POINTS
FOR THE DAYTIME VISIBILITY CALIBRATION CURVE

Time	Transmittance	Visual Range	
7-30-41	Per 250 meters	Feet	Kilometers
4:47 A.M.	0.15	1300	0.40
48	0.13	1200	0.37
49		1300	0.40*
50		1300	0.40*
51	0.15	1300	0.40
52	0.15	1300	0.40
53	0.16	1400	0.43
54		1400	0.43*
55		1500	0.46*
56	0.17	1400	0.43
57	0.17	1400	0.43
58	0.11	1400	0.43
59	0.10	1500	0.46
5:00	0.10	1400	0.43
01	0.10	1400	0.43
02	0.09	1300	0.40
03	-	-	-
04	0.10	1300	0.40
05	0.10	1200	0.37
06	0.10	1300	0.40
07	0.11	1300	0.40
08	0.11	1200	0.37
Average	0.124		0.409

*Not used in computing average visual range.

The value of the contrast threshold, ε, determined from these observations was 0.055. This value corresponds to the center line on figure 7.2 which is the minimum deviation for the points obtained exclusive of Weather Bureau and twilight points. The value 0.055 was considerably greater than the values from 0.01 to 0.02 generally accepted at that time. This value did, however, fall between the value 0.065 reported by Houghton for clouds and his value for fogs which is about one-half that for clouds [48].

The line for ε equal to 0.055 is a reasonable representation of the calibration points for the shorter visual ranges. It was considered as the daytime and twilight calibration curve of the transmissometer. There appears to be, however, a somewhat systematic departure of the points from this line with increasing visual range.

The lines $\varepsilon = 0.031$ and $\varepsilon = 0.098$ were chosen so that for any given transmittance the corresponding visual ranges determined from these two lines differ from that determined by the calibration line by plus and minus 20 percent, respectively. Similarly, the lines $\varepsilon = 0.234$ and $\varepsilon = 0.003$ give visual ranges equal to one-half and twice that of the calibration line. These lines are of assistance in studying the departure of the points from the calibration curve.

A classification of the calibration points according to the general illuminance, as determined by the transmissometer background readings, showed no systematic differences of visual range with illuminance. This apparent independence of the visual range of objects with illuminance is in agreement with previous investigations and theory. Even the twilight points in figure 7.2 show no systematic differences. Some of these points result from observations when it was so dark that the 25-candela lights could be seen farther than the marks. The computed average value of ε for the twilight calibration points was 0.044. This value of ε is less than that for the daytime value (0.055), whereas laboratory studies show ε increasing at low illuminances. Because of the spread of the values for the comparatively small number of twilight points, however, the difference between ε for daylight and ε for twilight cannot be considered significant.

The 4-foot-square marks were observed from distances between 0.15 and 1.0 kilometer. The corresponding angles subtended at the eye by the marks varied from 0.46° to 0.07°. Similarly, the large mark when observed subtended angles from 0.15° to 0.05°. Middleton [94] suggests that the least angular dimension of objects should not be less than 1° and that the maximum size of the nearer objects should not exceed 5°. However, it was frequently noted that the visibility of other objects, both larger and somewhat smaller than the marks, gave no indication that their size had any effect on their visual range. For example, observations on a power line pole to one side of the row of marks frequently indicated the same visual range as that given by the marks.

7.3.2 Arcata

Some observations were made by NBS* at Arcata in 1947 using a single fixed target and varying the position of the observer. These results are shown as the crosses on figure 7.3. Each of these points represents the average of data in a manner similar to that used at Nantucket Island.

This method of obtaining thresholds requires the assumption that the fog density is uniform throughout the space through which both the target is observed and the transmittance is measured. The greater part of the point spread in figure 7.3 was believed to be caused by the transmittance of the measured path being not representative of the path for observations; there is the possibility of both random and systematic sampling errors. To reduce the magnitude of these effects, observations were made during the 1948 fog season at Arcata using, when possible, a path of sight nearly parallel and very close to that of one of the transmissometers. When the visual range was 500 feet, the two paths were nearly identical. These particular observations are shown as circles on figure 7.3. The variations that can occur in visibility observations using human observers are quantitatively discussed in Section 4.2.2.

*Note: These observations were made by Douglas, who made more than half of the Nantucket observations.

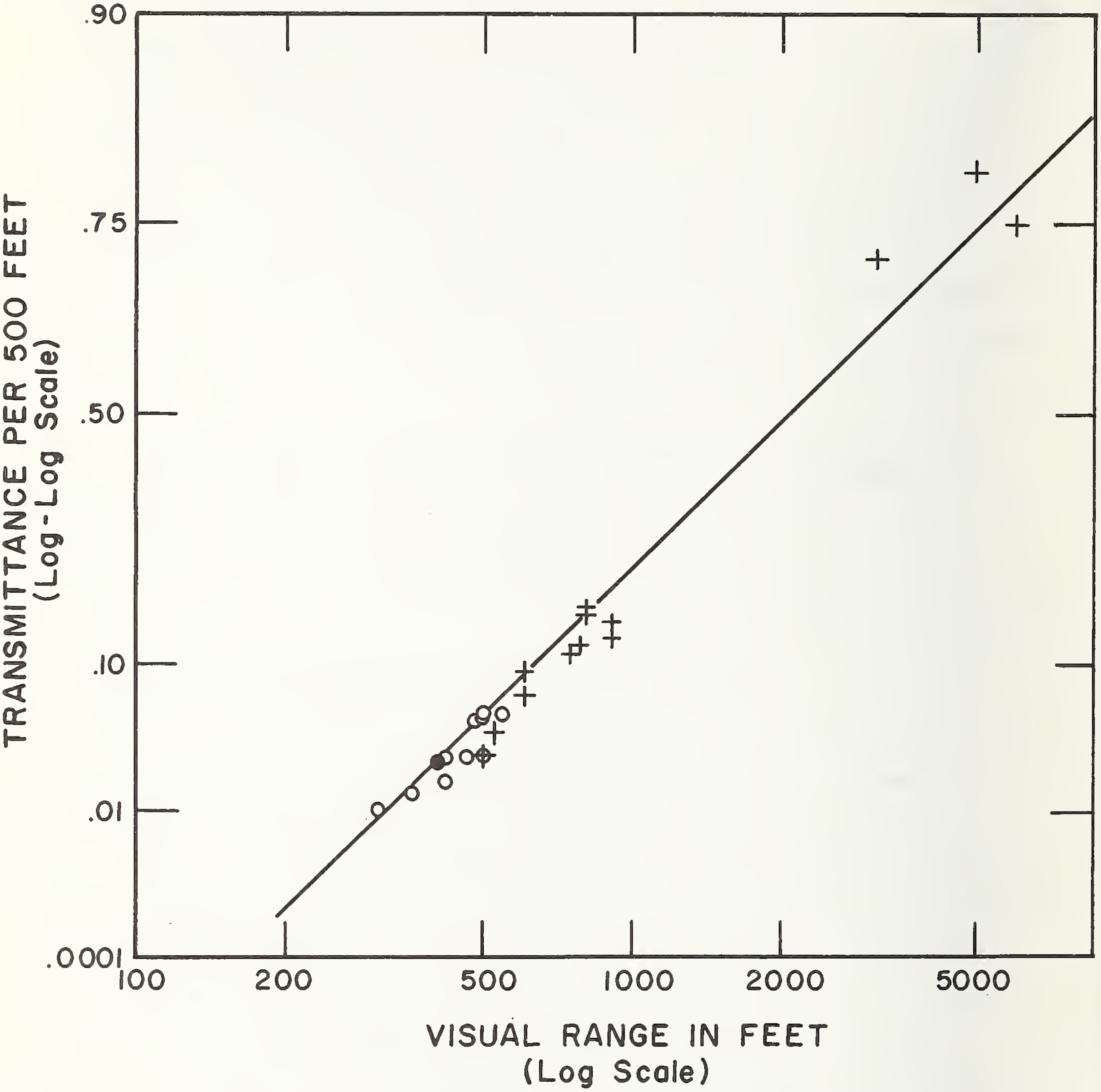

Figure 7.3 Visual range observations at Arcata of a single fixed dark object obtained while varying the position of the observer. 1947 results are shown as crosses. Results in 1948, shown as circles, were obtained using a path of sight nearly parallel and very close to the transmissometer baseline. The straight line shown represents the transmissometer calibration curve obtained at Nantucket.

7.3.3 Washington National Airport

Only those data which met the following criteria were used in threshold computations:

1. The visibility of the runway observer, looking north, was 3 miles or less. (All visibility determinations used in the determination of ε were for the north quadrant.)

2. The visibility in all quadrants did not vary more than 1/8 mile from that of the north quadrant.

3. The observer's visibility for the preceding observation and the following observation in the north quadrant did not differ by more than 1/4 mile from the observation used.

4. Transmittance as indicated by the transmissometer remained within ± 5% for the 15-minute period embracing the observation. (The value of transmittance used was based on a 4-minute average, the same as used by the Landing Aids Experiment Station in their application of transmissometer measurements to flight tests of approach and runway lights).

The cumulative frequency distribution of the contrast threshold values is shown on figure 7.4. The median of the observed values was 0.05.

7.3.4 Recapitulation of Daytime Visibility Calibration

Based on the observations obtained at Arcata, figure 7.3, and by the Weather Bureau, it would seem that a contrast threshold value of 0.05 is a better choice than the presently used value of 0.055. The value 0.05 is currently recommended by WMO [127].

7.3.5 Effect of Threshold on Day Visibility

In an atmosphere of transmissivity such that an observer, having a contrast threshold ε of 0.055, could just see a black object at a distance of 1/2 mile, under existing instructions [36] all observers having effective thresholds of from 0.039 to 0.080 would also report a visibility of 1/2 mile. At one mile, the tolerance would be from 0.037 to 0.064, and at 1/8 mile from 0.027 to 0.114. As evident from

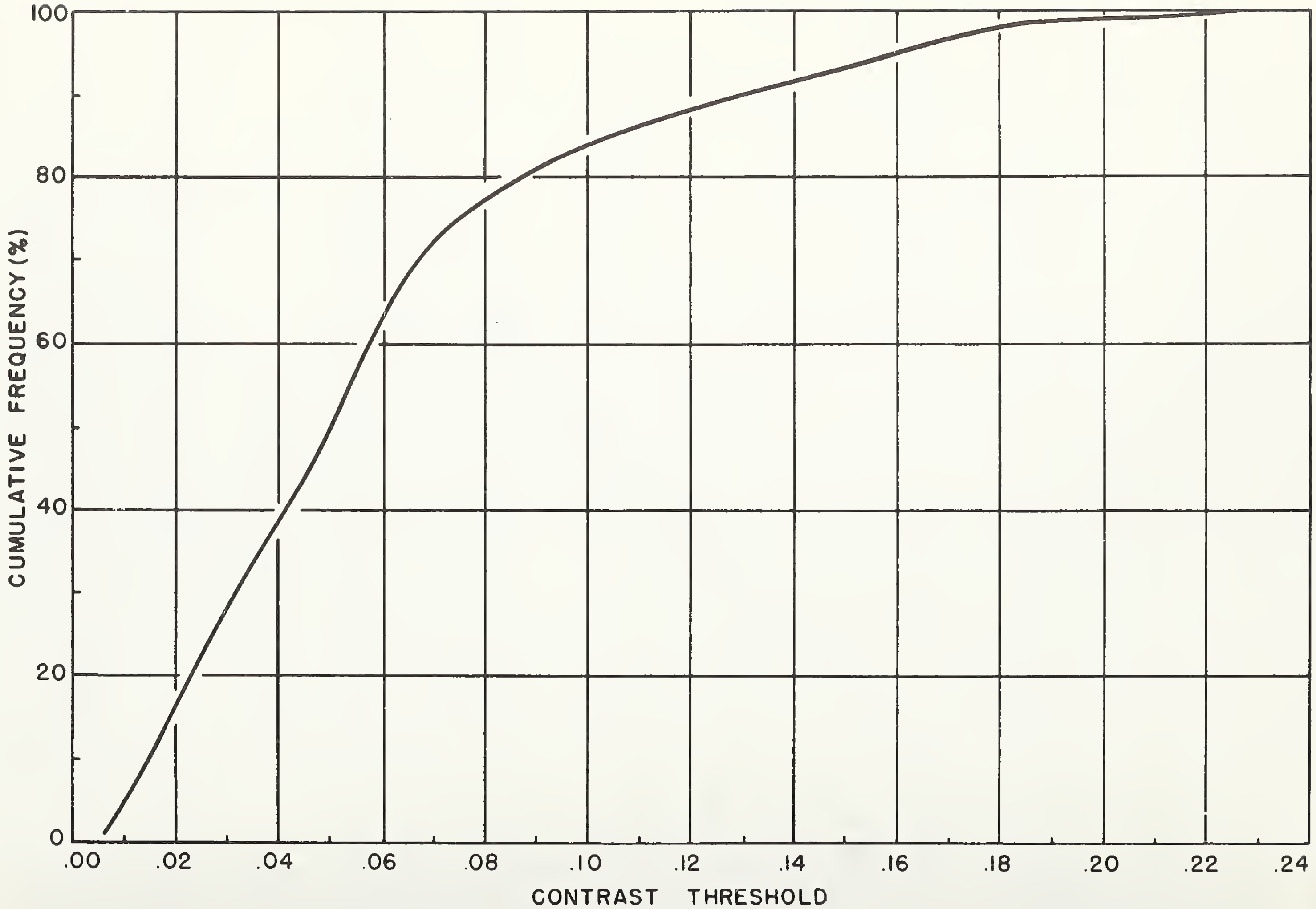

Figure 7.4 Cumulative frequency distribution of contrast threshold determined during Washington National Airport investigations [126].

figure 7.2, ε can vary from 0.031 to 0.098 while affecting visibility computed on the basis of $\varepsilon = 0.055$ by only ± 20%. Similarly, $\varepsilon = 0.234$ and $\varepsilon = 0.003$ give visibilities equal to one-half and twice the calibration line $\varepsilon = 0.055$. These examples show that the relationship between contrast threshold and computed visibility is not linear and are not intended to imply that the variations are unimportant.

7.4 DISCUSSION OF RESULTS - NIGHTTIME OBSERVATIONS

7.4.1 Nantucket Island

Figure 7.5 shows the results obtained from observations on 25 candela lights. The scales and symbols are similar to those used for objects by day, figure 7.2. Three curves are shown on figure 7.5, corresponding to:

Allard's law which states that the visual range of a light is the distance at which the light will produce a fixed illuminance threshold,

$$E = IT^V/V^2; \tag{4.24}$$

an assumption that the illuminance threshold varies inversely as the visual range,

$$S = IT^V/V; \tag{7.01}$$

and, for comparison, an equation where I_V/I is equal to the transmittance over the distance V,

$$I_V = IT^V. \tag{7.02}$$

Equation (7.02) may be considered as a form of Koschmieder's law in which contrast and contrast threshold are replaced by intensity and intensity threshold.

For all three curves, I = 25 candelas and E, S, and I_V have been set numerically equal to 0.052; E has the dimensions of illuminance and

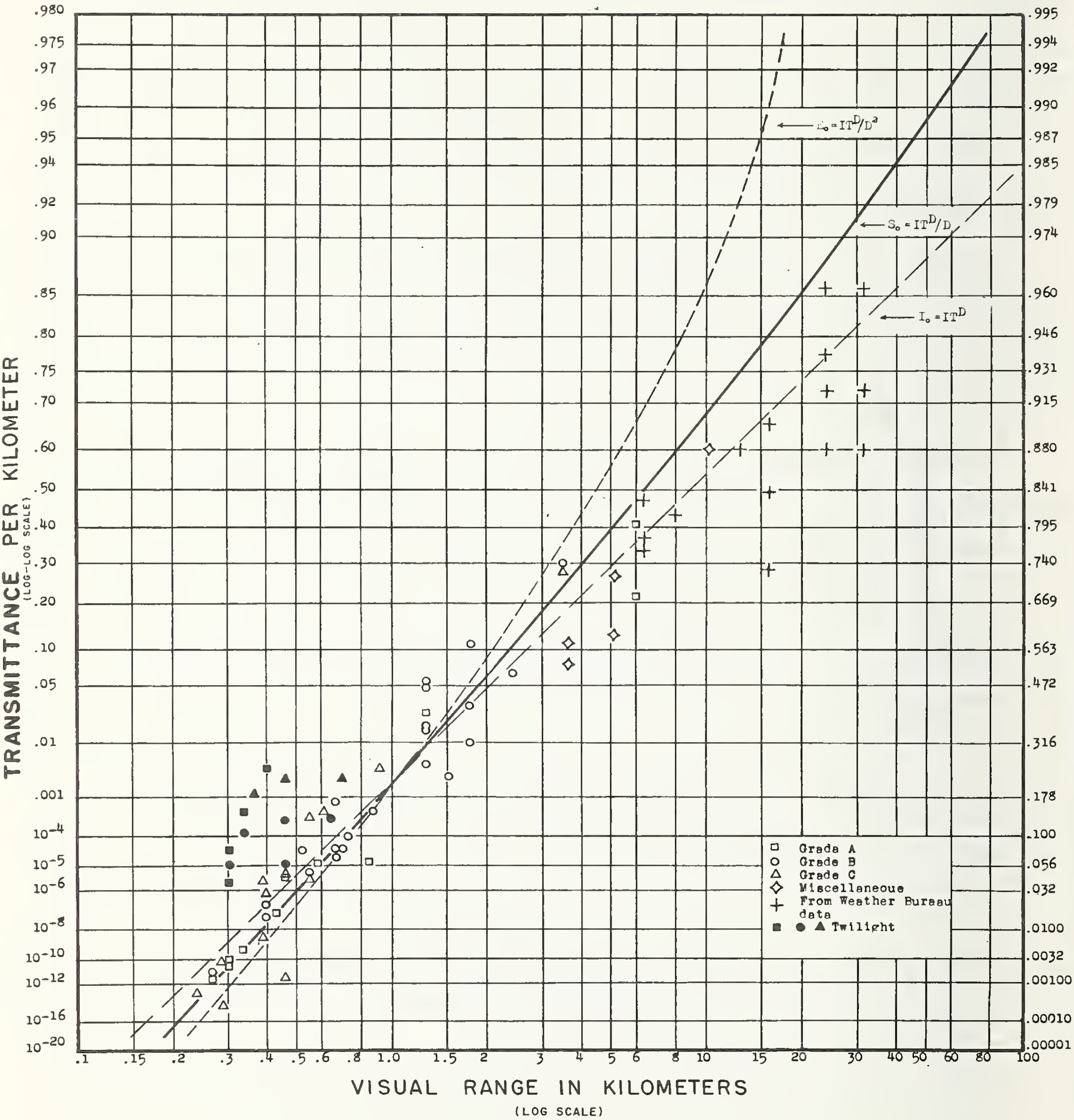

Figure 7.5 Nighttime transmissometer visibility calibration curves, based upon a light intensity of 25 candles, derived from data obtained at Nantucket Island [30].

is expressed in kilometer candles*, S has the dimensions of intensity per unit distance and is expressed in candelas per kilometer, and I_V has the dimensions of intensity and is expressed in candelas.

Equation (7.02), like Koschmieder's law, is represented by a straight line. The value for I_V/I was obtained in the same manner as ε was obtained for the daytime visibility calibration with $I_V = 0.052$ candelas.

The S curve provides the best fit for the calibration points on figure 7.5. This relation was first derived from observations made at Nantucket in 1940 on a calibrated lamp by two observers at different distances.

It should not be inferred from this statement that the illuminance at a point is not given by (4.24) but rather that the minimum perceptible illuminance is not a constant and is such a function of T and V that (7.01) represents the data more satisfactorily. From these data it appears that the illuminance threshold varies inversely as V, the visual range. Hence, if E/V is equal to E_o/V where E_o is the illuminance threshold at unit distance, and is set equal to 0.052 where V is in kilometers, then (4.24) is equivalent to (7.01). Note that when the mile is the unit of distance, S is equal to

$$S_{(mi)} = 0.052 \text{ cd/km} \times 1.61 \text{ km/mi} = 0.084 \text{ candela/mile} \qquad (7.03)$$

7.4.1.1 Rationale for Choice of Intensity of Lights

In obtaining a transmissometer visibility calibration curve for determining visual ranges at night, it is evident that consideration must be given to the intensity of the lights which will be used as marks. In this respect the visual range by night differs from that by day, for by day the visual range is substantially independent of the objects observed whereas the visual range of a light at night depends on the intensity of the light. Thus, for any given distance it is possible to choose the intensity of a light so that it will be at the

The kilometer candle and the mile candle are early units of illuminance traditionally used in signal lighting. In modern practice, one kilometer candle, which is one lumen per square kilometer, should be designated as 10^{-6} lux or 1 microlux. See Para. 2.1.6. Metric units were used by NBS and ANDB in their reports in the 1940's and 1950's with the expectation that the U.S. would soon adopt these units. However, the English unit mile candle (1 lumen/mi^2) continues to be used.

limit of visibility at night when the transmissivity is such than an object at this distance would be at the limit of visibility by day. (See section 2.3.13 and reference [94], for further discussion of the equivalence of day and night visibility.) If a transmissometer were calibrated by means of a system of such lights, the visibility calibration curve for the lights should be the same as that obtained for objects by day. The intensities of the lights required by this system for visual range in the region 20 to 40 kilometers are of the same order of magnitude as the intensities of airport boundary lights and street lights. The required intensities for the lights for visual ranges lower than 10 kilometers are less, however, and the intensities for visual ranges lower than 1 kilometer are much less than the intensity of any ordinary light used as a landmark and thus these landmark lights can be seen at greater distances than the indicated visual range. For example, when the transmittance is such that object visibility by day is 1 kilometer or less, the visual range of a 25-candela light by night is about twice this distance. This is evident from a comparison of figures 7.2 and 7.5, or from figure 7.9. It seems preferable, therefore, that in practice nighttime visual ranges should be determined from a visibility calibration curve which is based on lights having intensities comparable to those usually used as landmarks. Twenty-five candelas is about the minimum intensity of such lights. Frequently lights of greater intensity are used, especially for the larger visual ranges. The visibility calibration curve to be used to determine visibility at night should therefore be based upon the intensity of the lights which a pilot uses and is expected to see from various distances.

It should be noted that the intensity of these lights is such that the observers used foveal (cone) vision in determining their visual range. Foveal (cone) vision is also used by aviators, even at low light levels.

7.4.2 Arcata

In the preceding discussion, it was shown that assuming the illuminance threshold varies inversely as the visual range provides the best fit to the data on figure 7.5. From this it appears that an observer's threshold is affected by changes in the background luminance in the immediate vicinity of the lamp which are produced by the lamp itself. Under conditions of low background luminance, when an unscreened lamp is definitely above threshold, an area of illuminated fog surrounding the lamp is visible. As the apparent intensity of the lamp approaches threshold, this glow is generally no longer apparent and only the point source itself is visible. Nevertheless, there appears to be some sort of an effect from this unseen glow.

A few observations made by NBS at Arcata in 1947 are shown in figure 7.6 together with the transmissometer visibility calibration curve based on the Nantucket data (over the ranges shown, the calibration curve is nearly a straight line). The range of distances here is too small and the spread of points too large to determine whether Allard's law or the calibration curve provides the best fit. However, the data do show that the threshold used is the right order of magnitude.

This variation of the illuminance threshold with visual range can be considered as approximate only.

In 1954, NBS made comparative visual range measurements in fog at Arcata of two 25-candle lamps, one unshielded and one shielded so that only the light emitted in the direction of the observer was allowed to escape. There were times at night when the glow surrounding the bare lamp could be seen further than the direct light from either lamp. However, the distances at which the direct light from the two lamps could be seen was essentially the same.

7.4.3 Washington National Airport

In an attempt to be reasonably certain of a homogeneous atmosphere in the vicinity of the airport, the Weather Bureau subjected their nighttime observations to the same restrictions applied to the daytime observations; see Section 7.3.3. The median value of E determined from 94 observations was 0.045 kilometer candle. Figure 7.7 shows a cumulative frequency curve for values of S for these observations. S was computed from the relation S = EV. The median value obtained was 0.052 candelas/ kilometer which is identical with the value obtained at Nantucket and

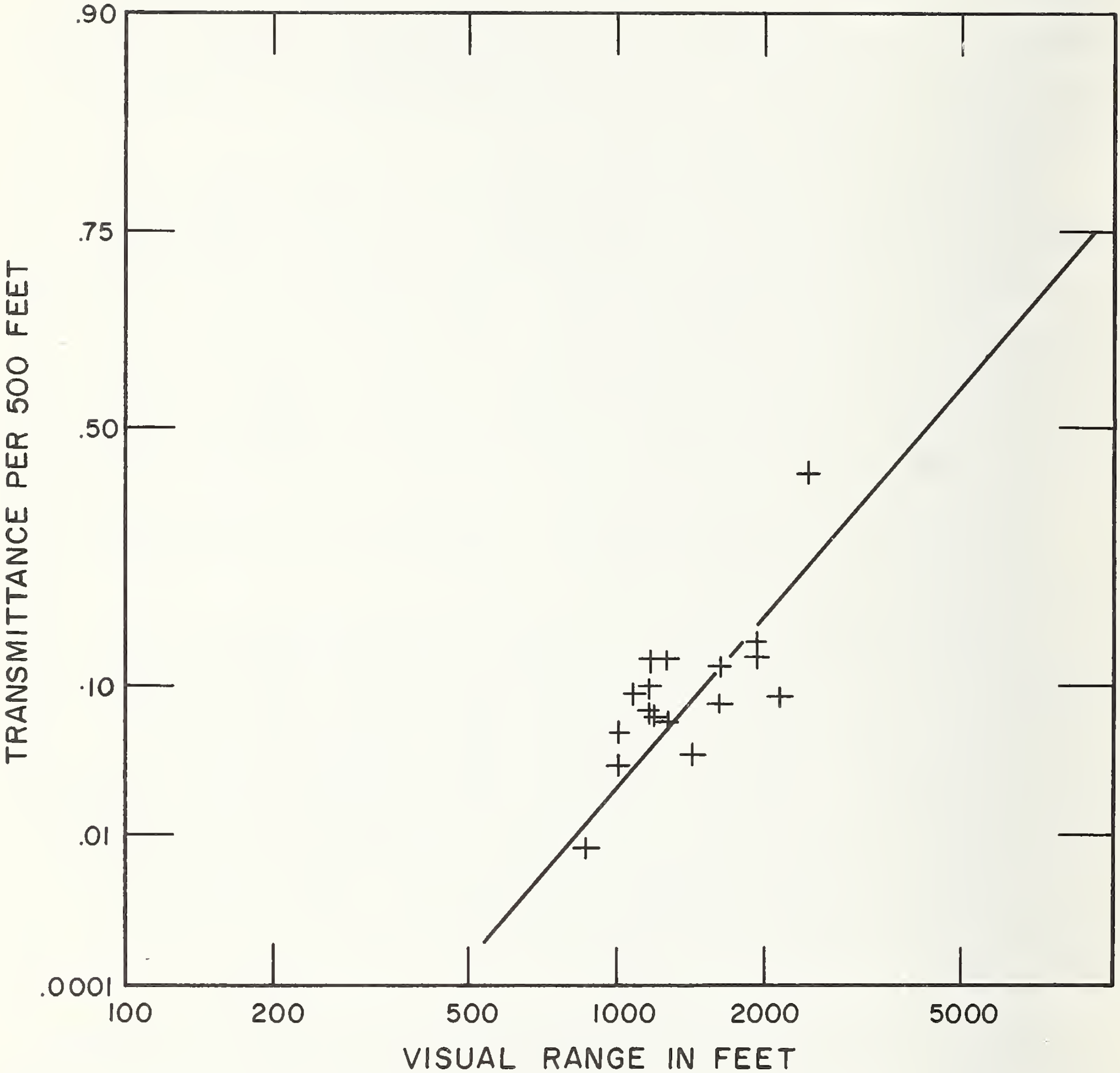

Figure 7.6 Visual range observations at Arcata of a single fixed 25 candela light obtained in 1947 while varying the position of the observer. The solid line is the transmissometer visibility calibration curve based on Nantucket data. As in Fig. 7.3, the abscissa is a log scale and the ordinate is log-log.

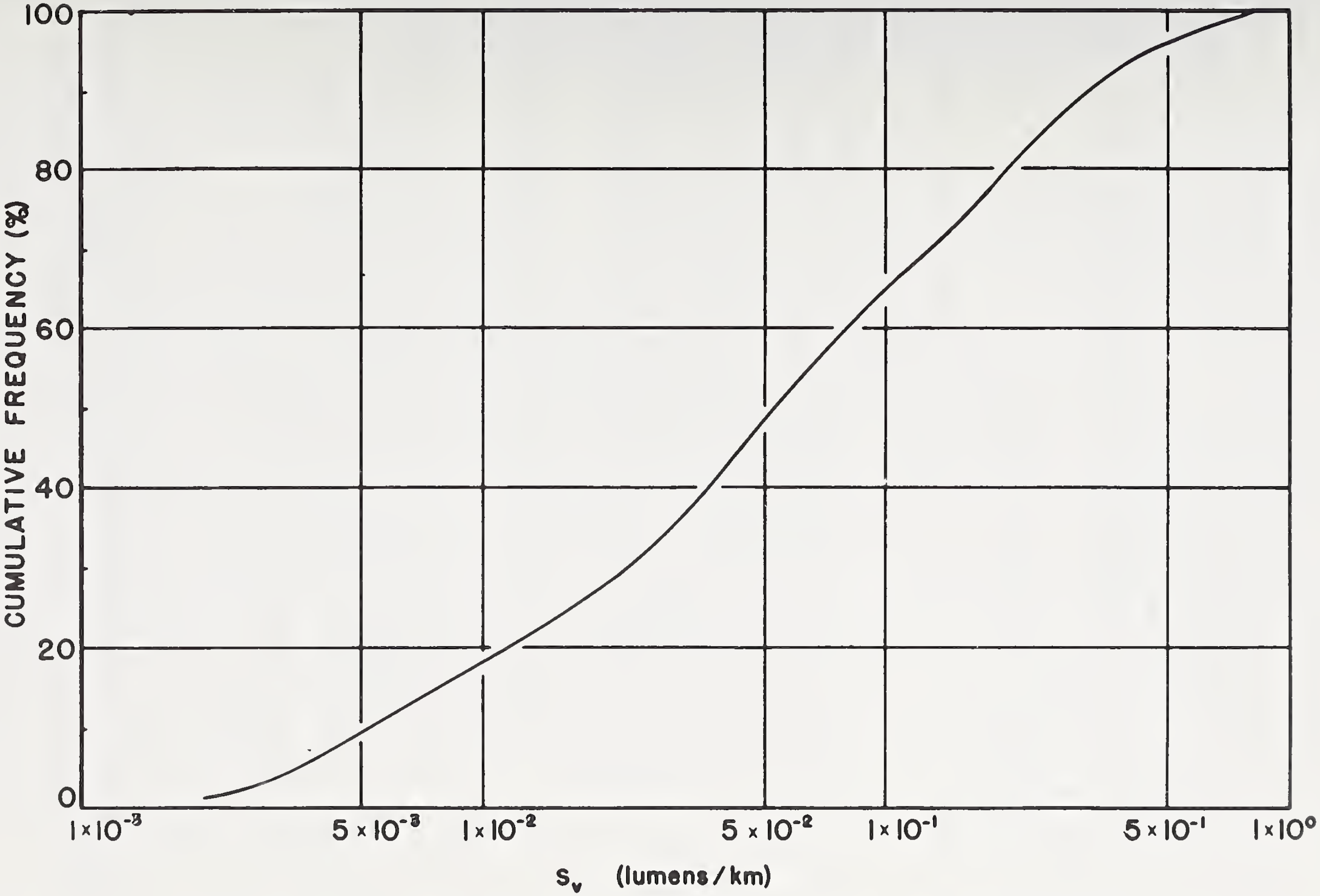

Figure 7.7 Cumulative frequency distribution of S_V obtained during Washington National Airport investigations [126].

now used in the night visibility calibration for the transmissometer.

7.4.4 Effects of Background Luminance

The illuminance threshold varies with background luminance, as shown in figure 4.4. The Weather Bureau measured the background luminance from the end of the runway location. Their measurements indicated background luminances of the order of 10^{-2} mL. This agrees roughly with unpublished measurements made by Douglas. At a later date, Simeroth [114] reported ambient horizon-sky luminances in the region of the airport (approach and runway lights off or at low intensity) which were also of the order of 10^{-2} mL.

7.4.5 Effect of Threshold on Night Visibility

Figure 7.5 shows three different nighttime transmissometer visibility calibration curves derived from data obtained at Nantucket Island. The three curves all yield identical values at a visibility of about 1 kilometer. Different values of threshold produce a family of curves of increasing ordinate scale with increasing threshold values. It is evident from figure 7.5 that the exact shape of the visibility calibration curve has little effect in the region 0.4 to 3 kilometers (0.25 to 2 miles) visibility. The curves on figure 7.5 are divergent and yield appreciably different results for greater visibilities.

7.4.6 Comparison of the Nighttime Illuminance Threshold Applicable to Meteorological Visibility and to Runway Visual Range

It is evident from Sections 7.4.1, 7.4.2, and 7.4.3 that different criteria were used in the establishment of the illuminance threshold applicable to meteorological visibility than to runway visual range.

Combining equations (4.24), (7.01) and (7.03) yields

$$E_t = S/V = 0.084/V \qquad (7.04)$$

where E_t is the illuminance threshold in mile candles and V is the visibility in miles. This equation provides for a variable, not fixed, threshold.

Thus, for a meteorological visibility of 1/8 mile, the illuminance threshold is 0.67 mile candle and for a visibility of 10 miles, the illuminance threshold is 0.0084 mile candle. This range of illuminance thresholds is considerably greater than would be expected from the changes in background luminance with visibility reported by Simeroth and the Weather Bureau.* They found that background luminances ranged from about 10^{-3} footlambert in clear weather to about 10^{-1} footlambert in fog. The curve of figure 4.4 indicates that such a change in background luminance would be expected to change the illuminance threshold by a factor of 3, not 80 as shown in the example cited above. This large change in illuminance threshold is presumably produced by a change in the glow surrounding the lights used as visibility marks due to changes in atmospheric transmittance. This glow is primarily produced by the light itself, as discussed in Section 7.4.2, and not by other lights in the surround.

In the computation of nighttime RVR, a fixed illuminance threshold of 2 mile candles was chosen in 1955 by the United States. This value has since been accepted internationally. As already stated, in Sections 3.9.1 and 4.4.8, this value was intended to be a conservative value applicable to typical ambient background luminances of less than 0.1 foot-lambert. The illuminance threshold of 2 mile candles is 4 times the classical value for mariners and pilots, 0.5 mile candle, and is 10 to 20 times the illuminance thresholds shown in figure 4.4.

At the time this threshold was chose, RVR was considered to be a meteorological quantity reporting conditions of atmospheric clarity to the pilot in terms more meaningful than either atmospheric transmissivity or meteorological visibility. No adjustments were made for changes in intensity of the approach and runway lights when changing the operating intensity step of the lights nor from changes in illuminance threshold with background luminance. Allard's law (4.24) was used instead of the transmissometer calibration equation (7.01) in the computation of visual range since there were no data to demonstrate the applicability of an equation similar to the transmissometer calibration equation to the RVR computation. Instead, there were several reasons to question its applicability:

*In this context the term "background luminance" refers to the luminance of the background around the airport, as seen by the meteorological observer, not the luminance of the approach zone and runway as seen by the pilot.

1. It was considered unsuitable for day and twilight conditions since the luminance of the glow produced by the approach and runway lights is small in comparison with the ambient background luminance,
2. Under nighttime conditions, the apparent luminance of the background of the lights upon which meteorological visibility observations are based is significantly lower than the luminance of the fog over approach or runway light systems, and
3. The illuminance threshold value chosen for RVR computations was significantly higher than that chosen for meteorological visibility computations and hence the two thresholds might be affected differently by changes in visual range and fog density.

At the time the RVR computers were designed (Section 3.9.5), the effects of a change in intensity of the lights with intensity setting were included in the RVR computation, but the effects of changes in fog luminance, with intensity setting, on the illuminance threshold were not.

7.5 COMPARISONS BETWEEN OBSERVED PREVAILING VISIBILITY AND TRANSMISSOMETER DATA - DAY AND NIGHT

The Weather Bureau compared their observations of the prevailing visibility with visibility determinations based on transmissometer measurements using the Nantucket visibility calibration curves. The results of the comparison are shown graphically in figure 7.8. The ordinate of each diagram shows the percentage of occurrence of cases wherein the differences between the visibilities computed from the transmissometer indication and the visibility observed by runway observer looking north was equal to or less than the given abscissa value. Graphs are shown for several ranges of visibility for day and for night.

In assuming that the runway observer reported the correct visibility, the data on figure 7.8 indicate that for visibilities of 1 1/2 miles or less the transmissometer correlates reasonably well with the Weather Bureau observations and there is no significant difference between day and night performance.

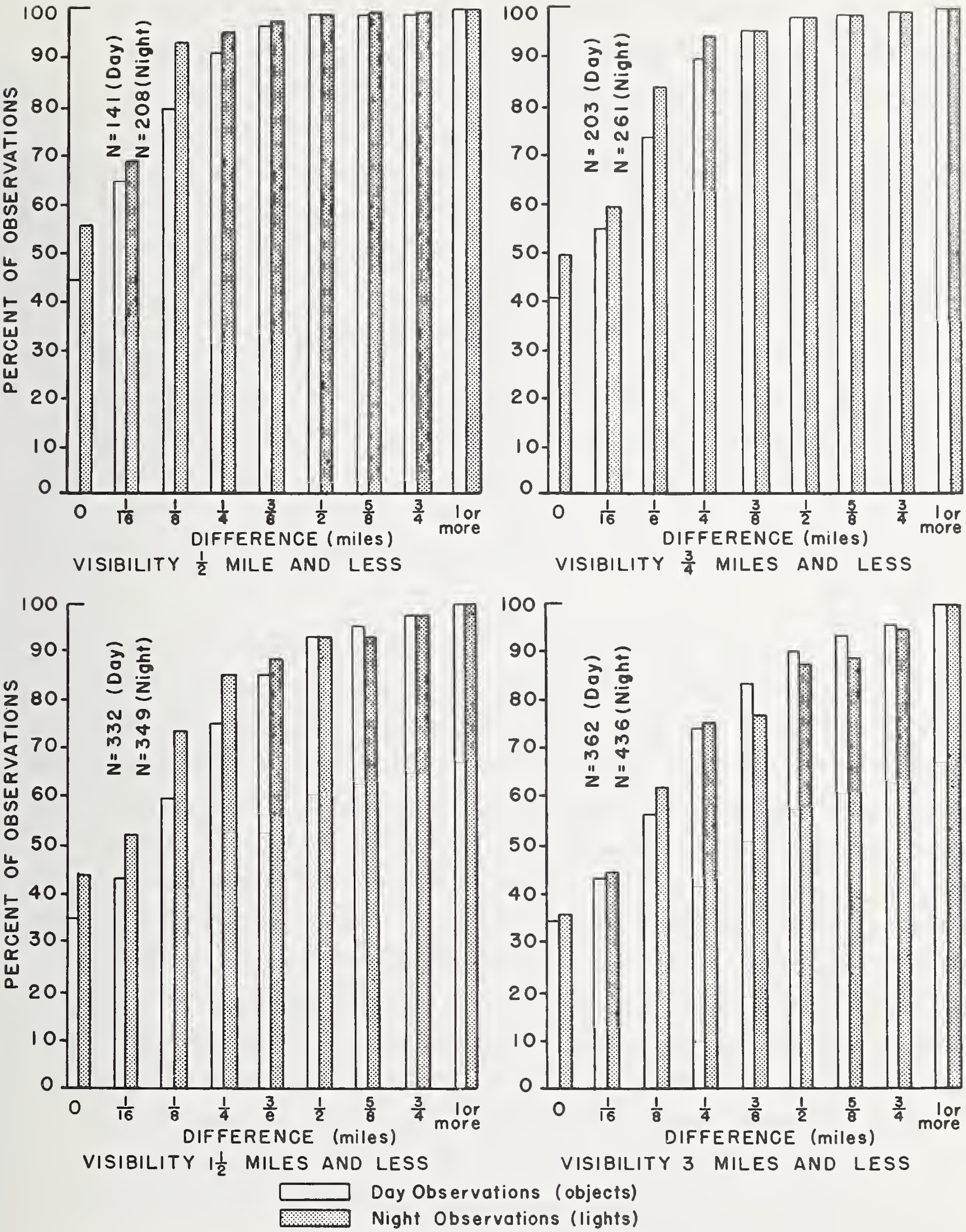

Figure 7.8 Cumulative frequency of various differences between visibility computed from transmissometer and visibility estimated by an end-of-runway observer during Washington National Airport investigations [126].

However, there are a number of limitations in comparisons of this sort that must be considered. Because of the subjective nature of the estimate, there is no guarantee that the observer is reporting the correct visibility. In addition to the recognized differences in threshold which are present among different observers, an individual observer's threshold can vary from time to time. However, as shown in Section 4.2.2, the effects of variations in observer's threshold are much too small to explain the differences of figure 7.8.

7.6 TWILIGHT TRANSMISSOMETER VISIBILITY CALIBRATION

Figure 7.9 shows both the day and night visibility calibration curves for a 500 foot baseline transmissometer. It is apparent from this figure that over the range of most concern, the night visibility is approximately twice the day visibility for a given transmissivity. The problem of transition from one curve to the other during twilight is of concern.

During both the NBS and Weather Bureau tests it was observed that, in the absence of appreciable changes in atmospheric transmissivity during the evening twilight, object visibility would hold relatively constant until sometime after which the lights could be seen further than the daytime markers, and then would decrease rapidly. Visibility of the lights gradually increased, then held relatively constant. In the morning twilight, the reverse sequence occurred. This process is discussed in more detail in reference [85]. During twilight conditions at Nantucket Island, NBS made simultaneous observations on both marks and lights. In figure 7.5, it is seen that the visibility of the 25-candela lights during twilight does not agree with any of the three curves, the lights being, as expected, less visible in twilight than at night. However, the daytime visibility calibration curve, figure 7.2, does agree approximately with the visibility of these lights during twilight, in addition to giving a satisfactory determination of the visibility of objects.

The Weather Bureau considered that one possible solution to the problem would be to take photometric measurements of the luminance of

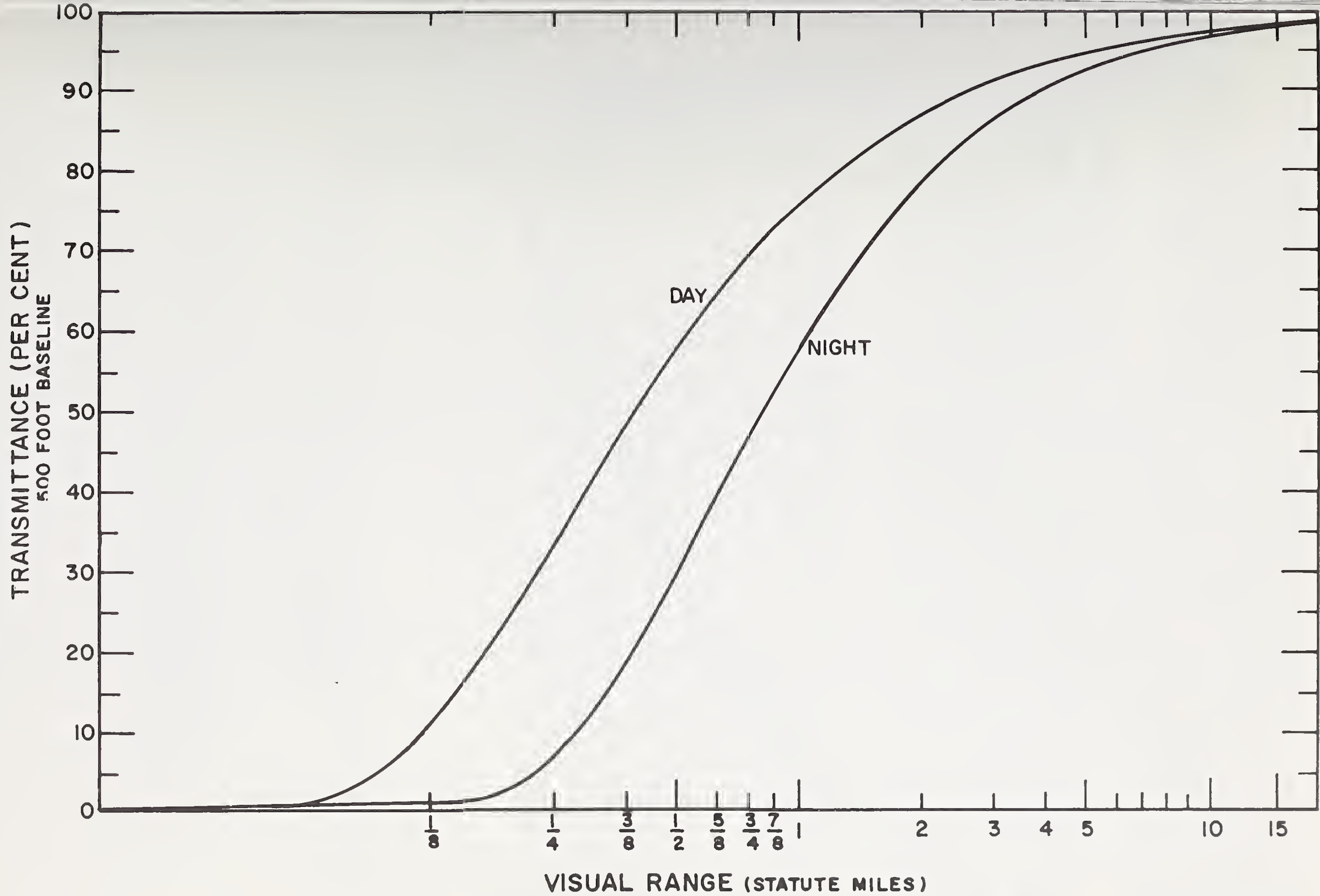

Figure 7.9 Day and night visibility calibration curves for a 500 foot baseline transmissometer.

the horizon sky and then use a visibility calibration curve based on the appropriate illuminance threshold [126]. The results of such measurements are shown on figure 7.10. A curve based upon data of Knoll, Tousey, and Hulburt [77] is also shown for comparison. There is only fair agreement between the points and the curve.

The possibility that the transition from daylight to darkness would follow a repetitious pattern from day to day such that an appropriate calibration curve could be chosen on the basis of time, without direct reference to photometric measurements, was also explored by the Weather Bureau [126]. Figure 7.11 shows the illuminance thresholds for all twilight observations plotted against time. As shown on the figure, there is no correlation.

In the U.S., the choice of which transmissometer visibility calibration curve to use during twilight has been approached pragmatically and conservatively. Consequently, the day visibility curve is always used during twilight. The night visibility calibration curve is used only during periods of darkness [103]. The problem of twilight visibility obviously increases with increasing latitude and the corresponding increase in the length of the twilight period. The solution adopted for the continental U.S., i.e., use the day visibility curve during twilight, is not applicable to latitudes somewhat greater than 50°.

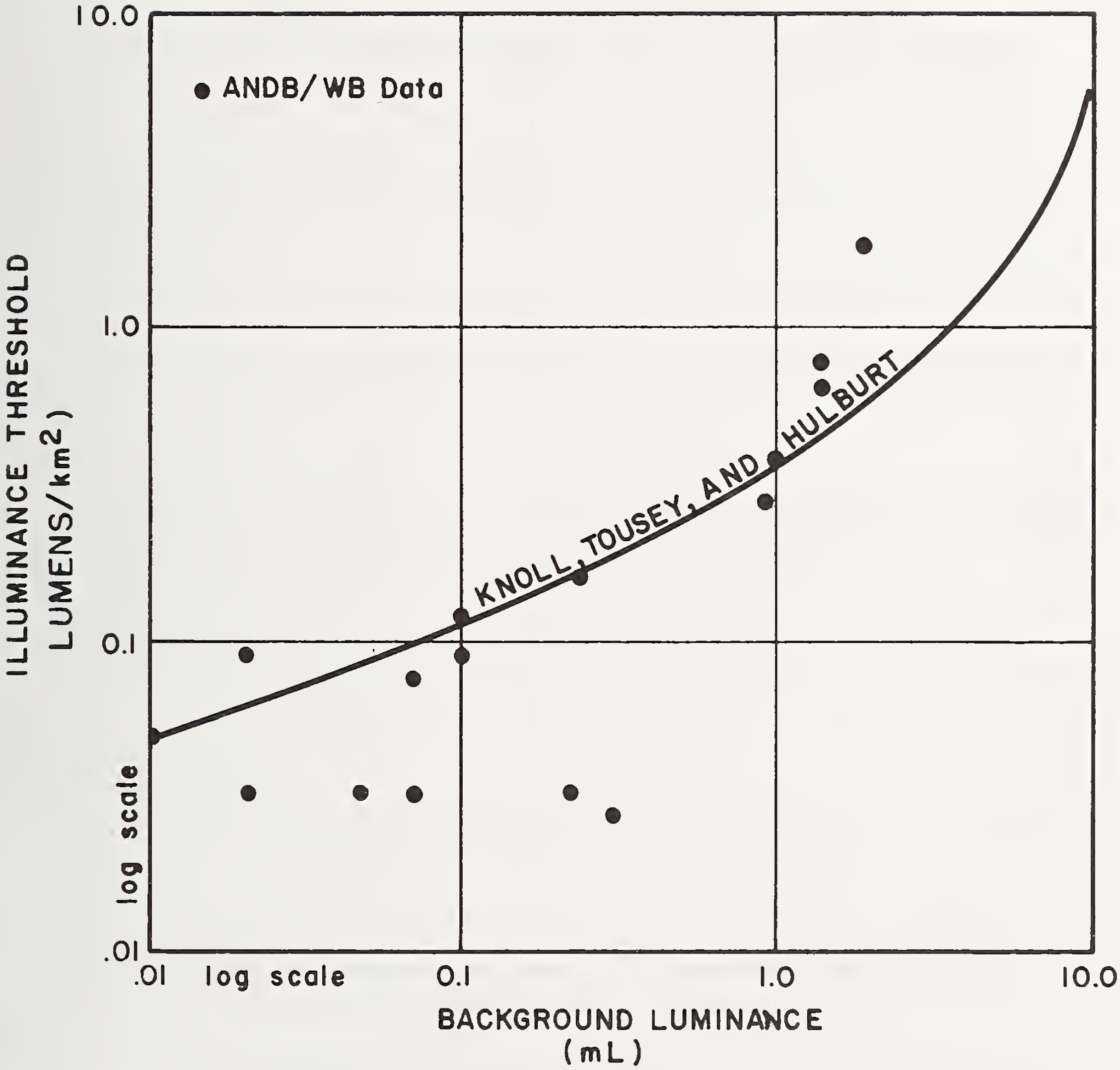

Figure 7.10 Illuminance thresholds based upon Washington National Airport measurements of horizon sky luminance during twilight. [126]

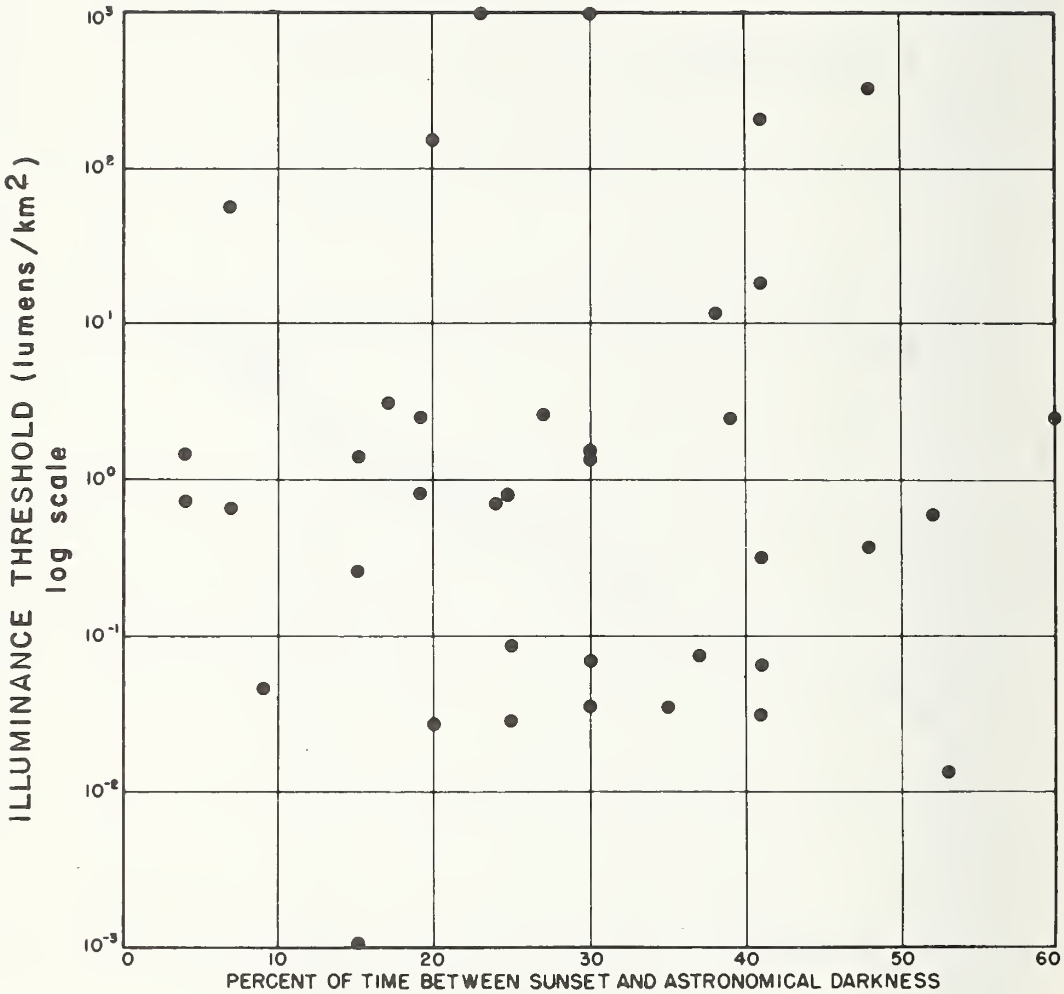

Figure 7.11 Illuminance thresholds computed from Washington National Airport twilight observations plotted against time [126].

8. MEASUREMENT OF CLOUD HEIGHT

8.1 INTRODUCTION

A beam of light incident on the base of a cloud is scattered to such an extent that at night the spot produced by a narrow beam of light is usually visible. This scattering provides a means for easily measuring cloud height. The simplest method consists of an observer measuring the angular elevation of such a spot of light at a fixed distance from the projector and in the vertical plane through the beam. The geometry of this arrangement is shown in figure 8.1. The angular elevation of the spot of light can be determined by the use of various types of clinometers such as alidades.

Let h be the ceiling height, L the baseline, θ_1 the elevation angle of the beam, and θ_2 the angular elevation of the spot.

Then

$$L = h \operatorname{Cot} \theta_1 + h \operatorname{Cot} \theta_2, \tag{8.01}$$

and the ceiling is

$$h = L/(\operatorname{Cot} \theta_1 + \operatorname{Cot} \theta_2). \tag{8.02}$$

If a fixed beam is projected vertically, as is U. S. practice,

$$\operatorname{Cot} \theta_1 = 0,$$

and

$$h = L \tan \theta_2 \tag{8.03}$$

The foregoing assumes that the projector and the clinometer lie in the same horizontal plane. Simple corrections can be made when they

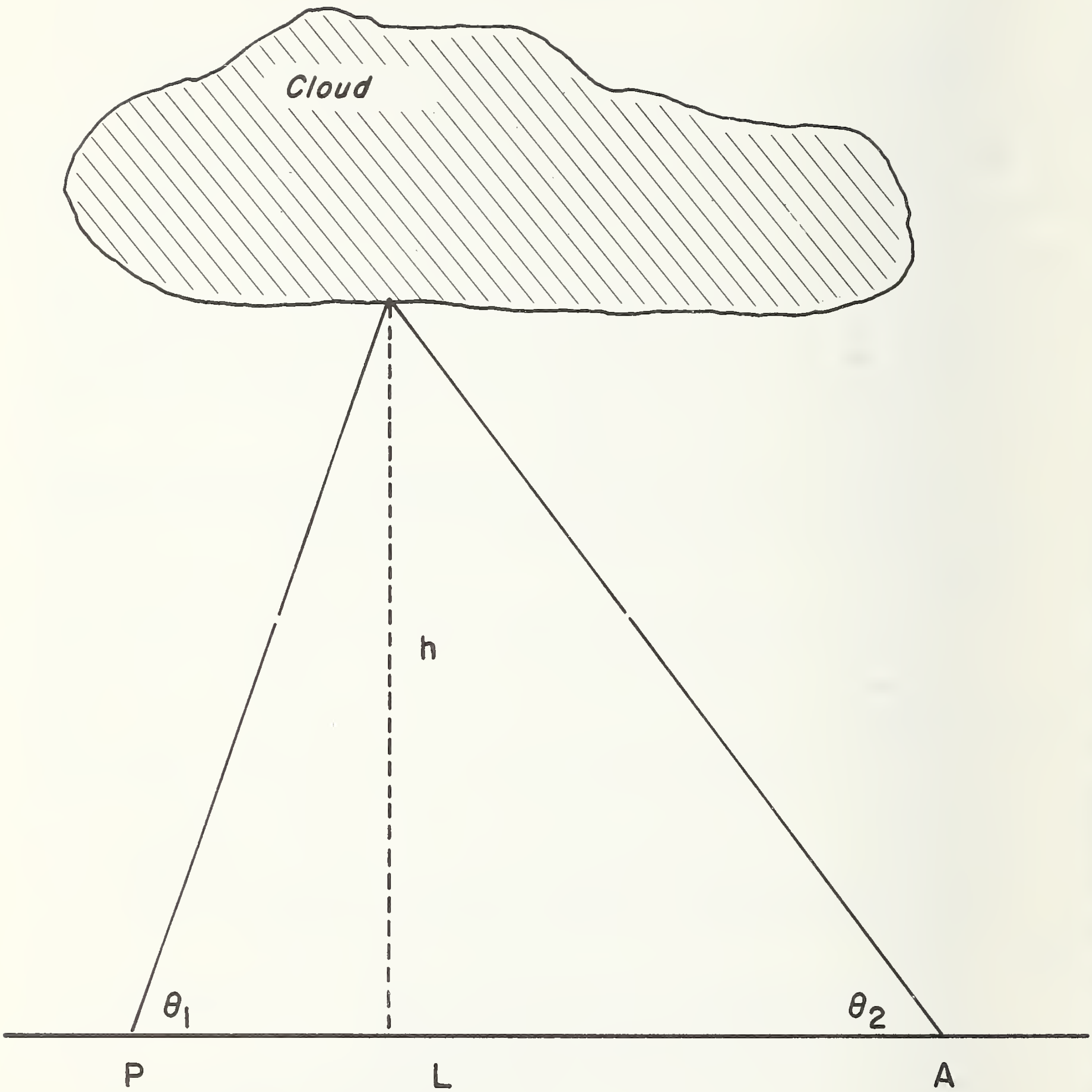

Figure 8.1. Schematic representation of cloud height measurement. Projector is located at P, observer/alidade is at A. In U.S. practice, the beam is projected vertically and $\theta_1 = 90°$.

are not horizontal [92].

Middleton discussed the theory of ceiling projectors, and their use for night measurements in 1939 [92]. He favored a baseline of 1000 feet and a projector angle of $\theta = \tan^{-1} 3.0 = 71° 34'$ for maximum accuracy to ceilings in the neighborhood of 3000 feet. Vertical projection of the beam gives somewhat greater accuracy to measurements of very high ceilings.

Since the underside of a cloud cannot be considered as a plane, diffusely reflecting surface, Middleton analyzed the luminance of the spot of light on the cloud for different ceilings. In discussing the results of his theoretical calculations for projection angles of 71° 34' and 90° under three different conditions of the atmosphere, he noted the following:

(1) When the visibility is low, 0.5 mile, the luminance of the spot falls off rapidly for heights greater than 1000 feet. The ceiling height which can be measured is thus severely limited by the obscuring power of the air beneath the cloud.

(2) For visibilities of 5 miles and greater there is a maximum luminance at about 1000 ft for the 71° 34' angle of projection and at about 700 ft for a 90° angle of projection.

(3) For visibilities of 5 miles and greater, the luminance does not vary over a range of more than 10 to 1 between 200 and 2500 feet. Within this range the 90° angle of projection produces higher luminances.

8.2 PHOTOELECTRIC DETECTION OF CLOUD HEIGHTS

The visual ceiling projector is limited to use at night. During the 1930's, Middleton initiated the first work on a photoelectric detector which would extend the use of the ceiling projector to the daytime measurement of cloud heights through the utilization of a modulated beam. Starting with this basic principle, Laufer and Roskett [88] developed the first working model of what is now referred to as the fixed-beam ceilometer. This instrument successfully detected dark overcast clouds at an elevation of 9000 feet. A subsequent improved version [37] was successful in detecting clouds at 20,000 feet during the daytime.

8.2.1 Selection of Baseline Length

The length of the "baseline" i.e., the horizontal distance between the projector and the detector, is selected with reference to the range of greatest accuracy desired in a given ceilometer installation. The principles on which this selection is based were outlined by the Landing Aids Experimental Station [85].

As previously stated,

$$h = L \tan \theta \tag{8.03}$$

where h is the ceiling height, L is the baseline, and θ is the angular elevation. If dh is the error in h, then the ratio dh/h is the relative error;

$$dh = L \sec^2\theta \, d\theta , \tag{8.04}$$

$$\frac{dh}{h} = \frac{d\theta}{\sin\theta \cos\theta}, \tag{8.05}$$

$$\frac{dh}{h} = \frac{2d\theta}{\sin 2\theta}, \tag{8.06}$$

From (8.06) it can be seen that the greatest accuracy in the measurement of ceiling height (minimum relative error) occurs when the denominator of the right hand side of the equation is at a maximum. Since this occurs when $2\theta = 90$ degrees, the greatest accuracy of measurement is achieved at the 45 degree angle of scan, i.e., where the ceiling elevation is equal to the length of the baseline.

In installations with a long baseline, a small change in angle of scan at low elevations is equivalent to a relatively large change in the reported ceiling height. Therefore, extremely low ceiling measurements cannot be accurate if an excessively long baseline is employed. Conversely, when short baselines are used, the accuracy of low-ceiling measurements is improved at a sacrifice in the precision of measurements of high ceilings.

Figure 8.2 shows the relationship between angles of scan and the equivalent ceiling with various lengths of baselines, as determined using equation (8.03).

An argument is sometimes made that, since the ceilometer indicator can be read to an accuracy of about 1 degree, a ceilometer with, say, a 1500 foot baseline is adequate for the measurement of low ceiling height, e.g., in the range of 300 feet. From a mathematical viewpoint this seems correct, since reporting increments in this range are 100 feet. An examination of the projection angles listed in table 8.1, corresponding to cloud heights at the changeover points to the next reportable increment, reveals that the difference between these angles, about 1.8 degrees, is indeed greater than 1 degree.

TABLE 8.1

PROJECTION ANGLE θ CORRESPONDING TO SELECTED CEILING HEIGHTS h FOR A 1500 FOOT BASELINE CEILOMETER

h (feet)	θ (degrees)
250	9.5
300	11.3
350	13.1

However, under conditions of low visibility, which often accompany conditions of low ceiling, the ceilometer indicator can no longer be read to an accuracy of 1 degree because:

a. The irradiance at the detector, produced by light scattered from the cloud base, can be greatly attenuated during periods of reduced visibility, thereby reducing the signal to noise ratio, and
b. Scattered light effects broaden the angle of return, making it more difficult to determine the angle of maximum response.
c. When the sub-ceiling fog is sufficiently dense, the upper portion of the projected beam is attenuated to a level where the detector receives no meaningful signal from the cloud base. However, in dense fog, the ceilometer response is an indication of vertical visibility.

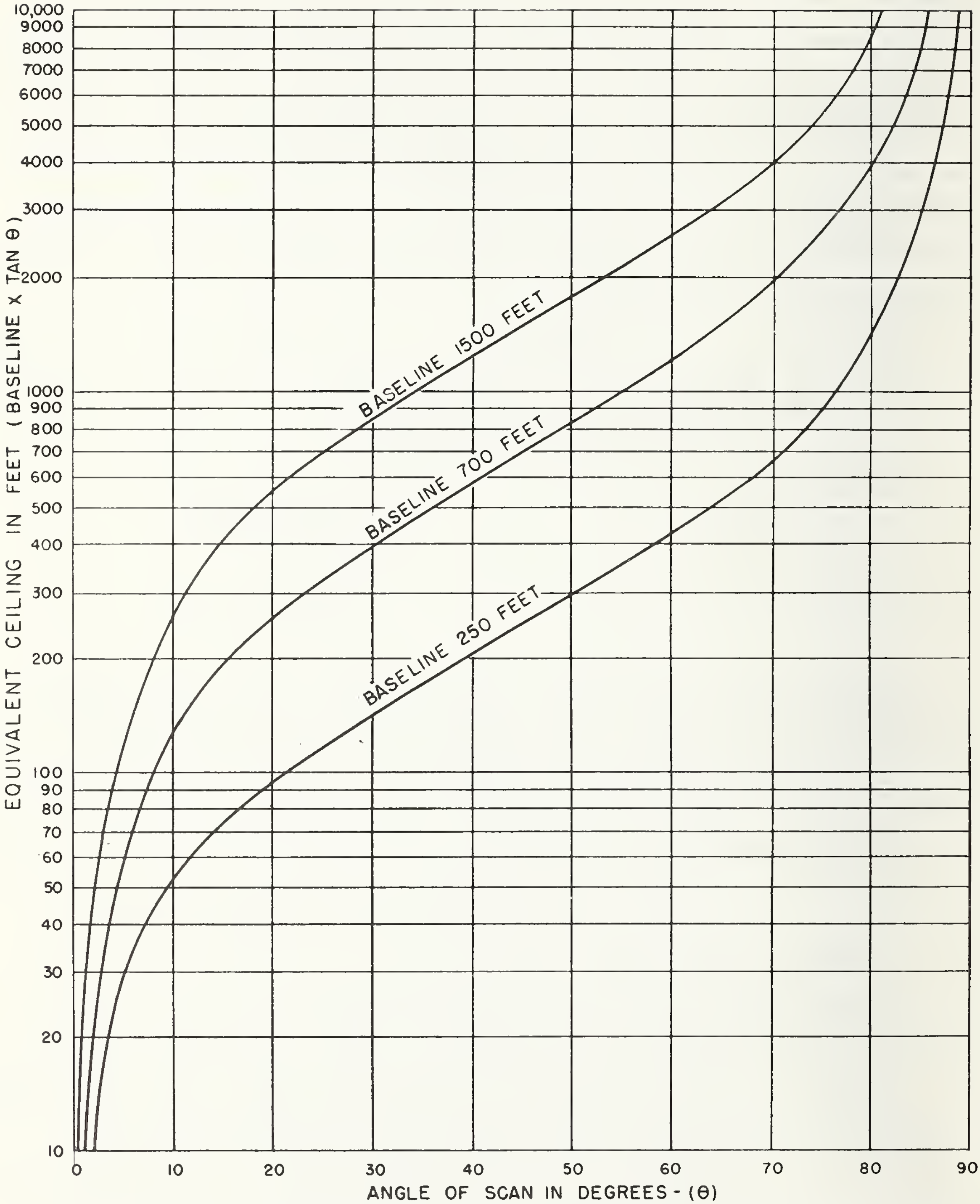

Figure 8.2 Ceilometer operation - angles of scan vs. equivalent ceilings for various baseline lengths [85].

The length of a ceilometer baseline must be chosen with reference to the objective of the intended installation, i.e., whether the ceilometer installation should serve as a general observational tool for large-scale synoptic analysis or as an operational aid in determining the precise values of extremely low ceilings in the approach zones of instrument runways.

The length of the baseline for purely operational installations should be selected to afford maximum accuracy at the critical cloud heights to be measured, usually near the minimum ceiling established by the regulatory authorities for aircraft operations at the given airport, and with reference to the density of fog or other obstructions to vision that may reduce visibility to the established local minimum for authorized aircraft operations.

8.3 FIXED-BEAM CEILOMETER

The advent of the fixed-beam ceilometer in 1941 added much to the precision and utility of cloud-measuring devices. It provided a means of automatically measuring and recording cloud heights, both night and day. The essential components are a vertical projector, a photoelectric detector which scans the modulated vertical light beam, an amplifier, and a recorder that provides a permanent record of the signal scattered from the light beam by the cloud particles and picked up by the detector. The height from which maximum response is obtained is used as the cloud height. The geometry of this fixed-beam ceilometer is shown in figure 8.3. The projector (vertical beam) consisted of a 1000-watt, water-cooled mercury-arc lamp located at the focus of a 24-inch parabolic mirror having a focal length of 10 inches. The ac operation of this lamp provided 95% modulation. An electronic synchronous switch was used to eliminate the effect of the varying background luminance of the clouds.

The Weather Bureau began using the ceilometer for operational purposes in 1943 and by 1953 had 140 in operation at civil airports throughout the United States and its possessions. An additional comparable number were also in use at military airports.

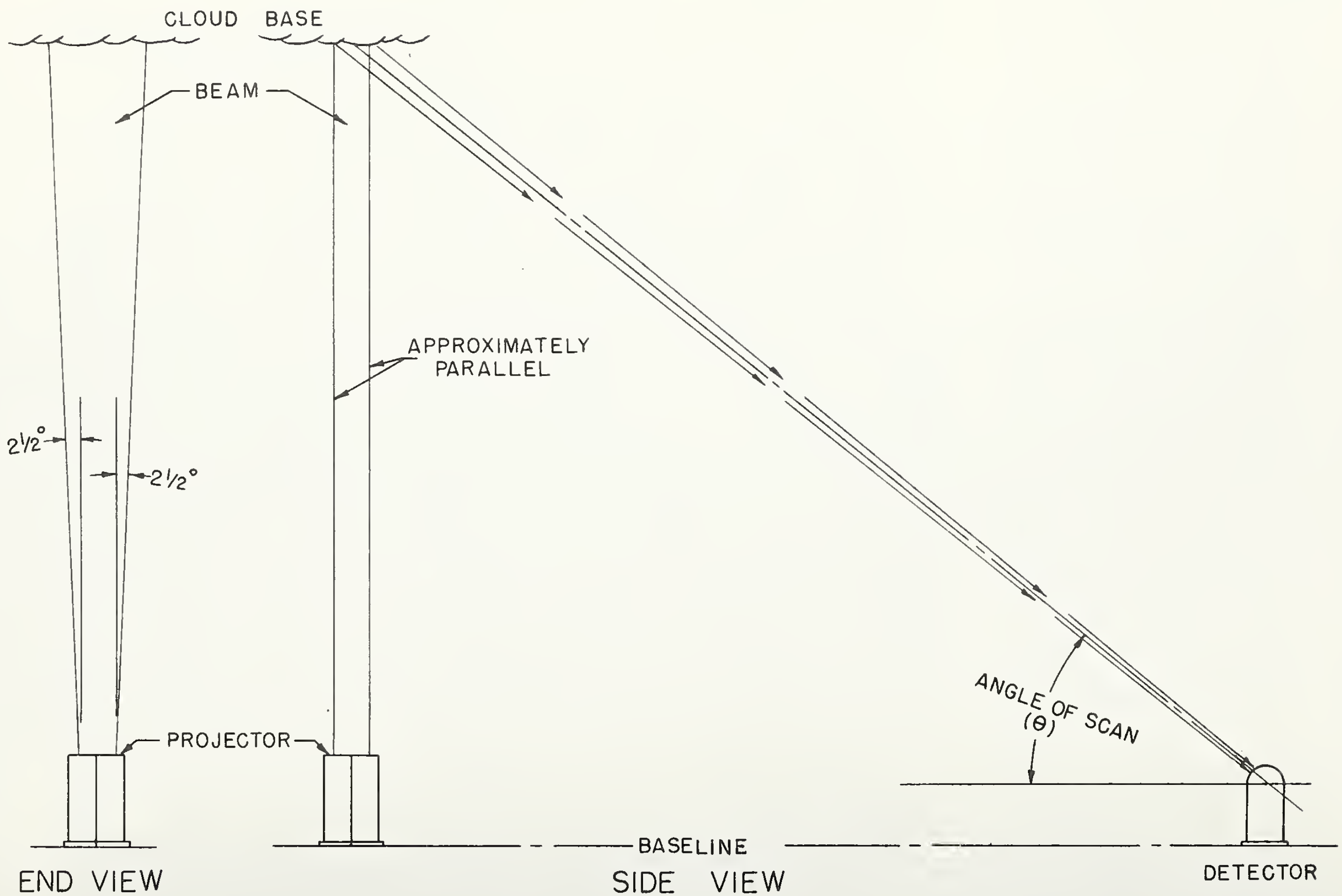

Figure 8.3 Geometry of fixed-beam ceilometer [85].

During the 1940's, activity at LAES included the testing and development of ceilometer models produced by various companies. (See figure 3.4 showing their locations at Arcata). The 1947 season included tests to compare the ceilometer indications with balloon height observations [84]. In relating balloon heights to significant ceilometer readings, mean values of similar observations taken during a given scanning cycle were used. Some of the results are shown in figure 8.4. Subsequent tests of the 700-foot baseline Crouse-Hinds instrument, furnished by the U.S. Weather Bureau, and a 250-foot baseline General Electric instrument, furnished by the U.S. Navy disclosed minor design deficiencies which were corrected as the evolution of the ceilometer continued [85].

8.4 ROTATING-BEAM CEILOMETER

In the early 1950's the Instrument Division of the Weather Bureau developed a new type of ceilometer based on the same general principles as the fixed-beam model -- that is, after the angle of maximum response from a light beam has been measured, the cloud height is computed by triangulation. The new instrument was different, however, in that the detector was directed vertically and the light beam swept the receiver-acceptance cone. A schematic diagram of the rotating-beam ceilometer is shown in figure 8.5.

In general, a rotating-beam ceilometer offers the following advantages over a fixed-beam [125].

(1) It is faster. The fixed-beam ceilometer was designed to give two indications per 12 minutes, whereas the rotating-beam ceilometer was designed to give an indication every 24 seconds.

(2) Because the electronic circuits are less complicated, the unit is less expensive, requires less maintenance, and is more easily installed.

(3) It is more economical to operate, due to its lower power consumption.

(4) Lamp life is much greater.

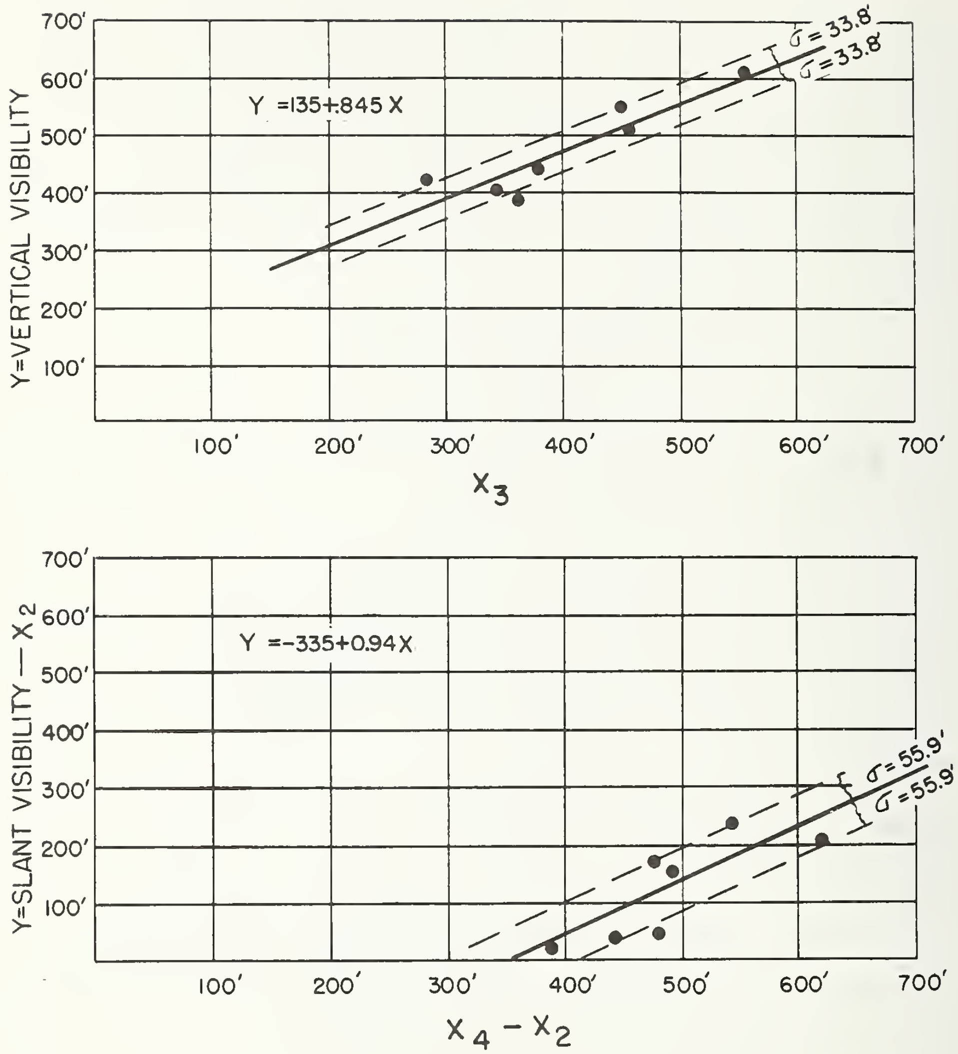

Figure 8.4. Some relationships between observed balloon heights and significant ceilometer signals from tests at Arcata. X_2 is the height corresponding to maximum ceilometer signal, X_3 corresponds to a beginning constant signal after decreasing from a maximum signal and X_4 corresponds to a height above X_3 at which the signal disappears. The slant visibility observer was stationed 700 feet from the balloon anchor point. The least squares equations and standard errors of estimate are also shown [84].

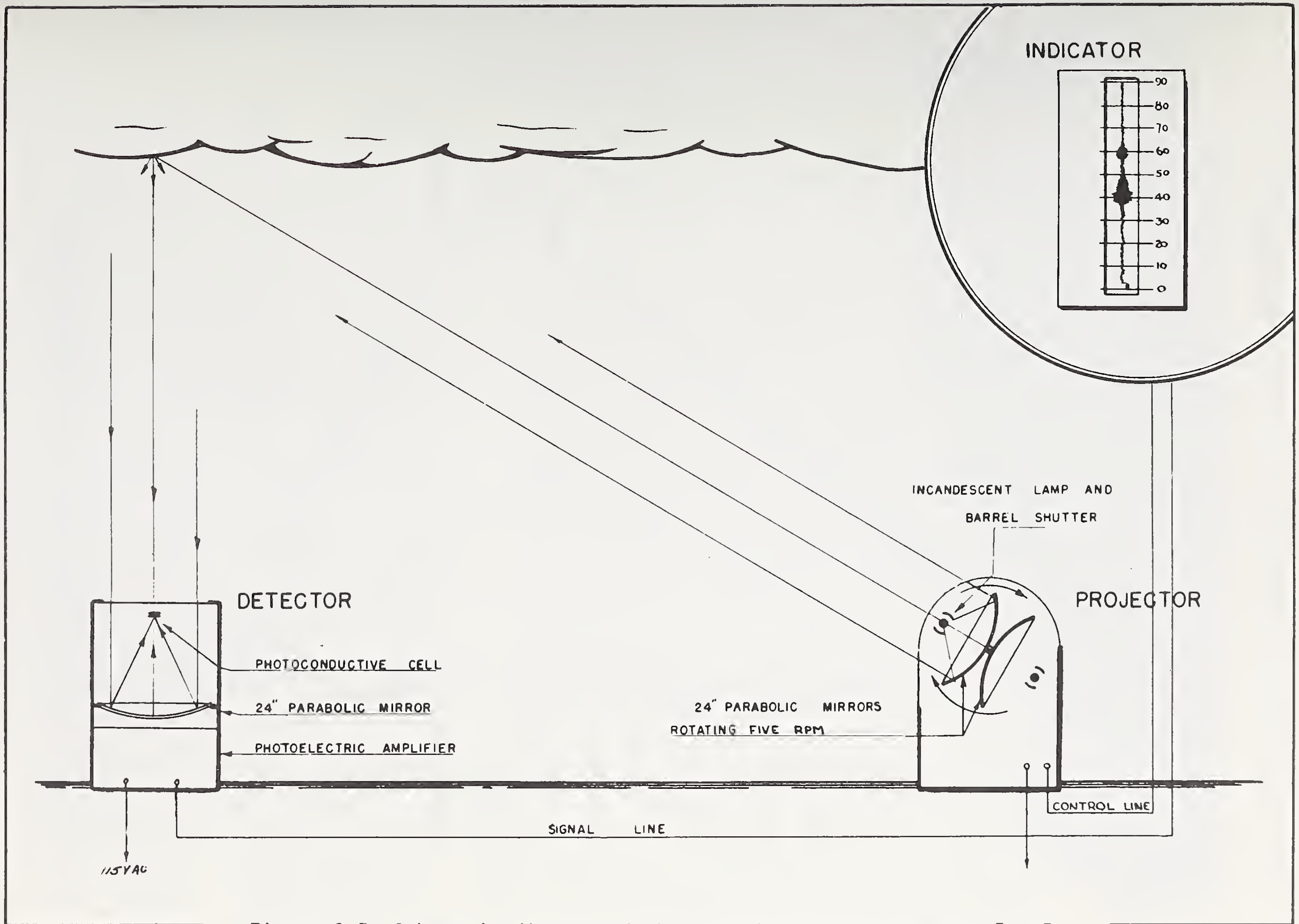

Figure 8.5 Schematic diagram of the rotating-beam ceilometer [126].

8.5 COMPARISON OF ROTATING-BEAM WITH FIXED-BEAM CEILOMETER

Much of the material in this section has been extracted from references [125, 126]. The information obtained during these comparisons is illustrative of the problems due to the inherent variability in cloud base height.

The measuring methods of the rotating-beam and fixed-beam ceilometers are fundamentally the same. The measurements are made by simple triangulation in both cases so that, other things being equal, the cloud heights measured by both instruments should be identical. However, the spectral characteristics of the lamps and the photocells employed in the two systems differ. The fixed-beam projector utilizes a mercury-vapor quartz-tube lamp with a detector photocell whose sensitivity is at a maximum in the visible spectrum near 0.45 micron (450 nm). The rotating beam utilizes an incandescent lamp rich in infrared, with a detector photocell whose maximum sensitivity with filters is beyond the visible spectrum in the near infrared (1.5 to 2 microns). In the past, all cloud-height or ceiling measurements, such as with ceiling balloons, ceiling lights, and fixed-beam ceilometers, have been made by methods employing some form of visible light transmission or scatter. The fact that the rotating-beam system utilizes light beyond the visible spectrum brought up the question of the validity of its measurements.

Comparisons of the ceilometers in the 1950's were designed to determine whether cloud-height measurements made by the rotating beam, using an infrared photocell, were compatible with those made by the fixed beam using a visible light cell. Some of these tests were conducted as part of the transmissometer-ceilometer program at Washington National Airport. Figure 3.12 shows the equipment layout.

The primary experiments, however, were conducted in 1952 at the Silver Hill Observatory in Maryland. Figure 8.6 is a perspective diagram of the ceilometer layout. R refers to a rotating-beam and F to a fixed-beam ceilometer. It can be seen that the ceilometers do not measure the same point on the clouds. However, due to

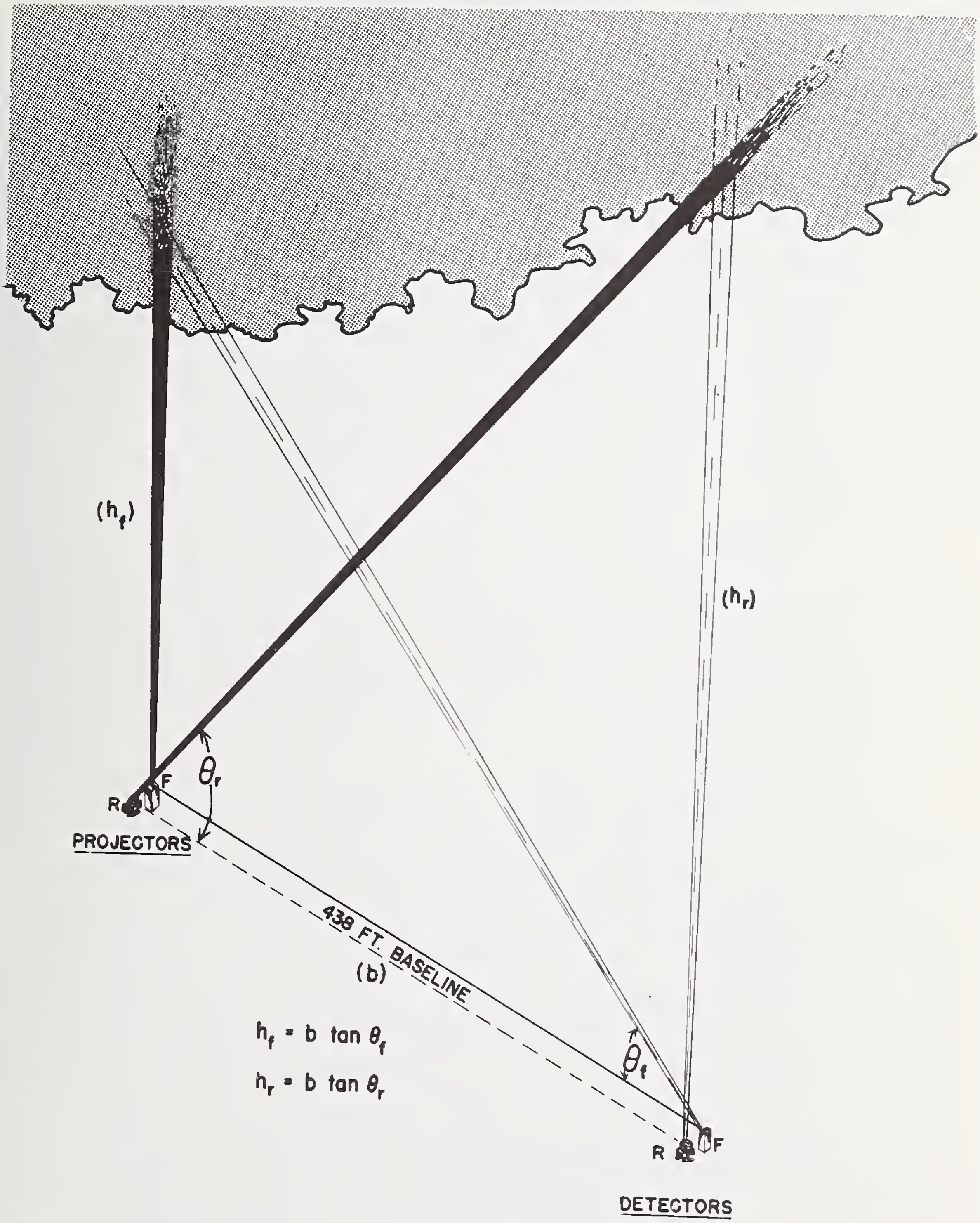

Figure 8.6 Ceilometer layout at Silver Hill Observatory, Silver Hill, Maryland [125].

difficulties in preventing interference between the two units, it was not feasible to have the components so situated that they could make independent measurements of the same point of the clouds. It was thought the separation did not materially affect the results of the comparisons, because the distance of separation was relatively small.

The fixed-beam ceilometer used in the tests was a conventional instrument of the type then in common use in the United States, with the exception that its scanning cycle was twice as fast as normal. It gave two measurements every six minutes and was equipped with a reversing switch, so that any scan could be stopped and reversed at will by the observer. During these comparisons, the reversing switch was used to provide as many discrete measurements as possible, so that the frequency of measuring shown on the following diagram is not representative of its normal use.

Figure 8.7 shows a comparison of heights corresponding to the maximum reactions of the two ceilometers. The comparisons indicate that although the rotating-beam ceilometer gives greater detail, the two systems are compatible in that there is no systematic difference between them. The diagram points up the large variations in low-level cloud base structure.

The diagram also shows the need for frequent spot checks, if measurements are to be made of all significant points of the contour of a cloud base as it passes over the instrument. The line connecting the seven spot measurements of the rotating-beam ceilometer following minute 76 probably gives a reasonably accurate representation of the cloud-base contour passing over the ceilometer at that time. On the other hand, it is very unlikely that the line connecting the ten spot measurements of the rotating-beam ceilometer following minute 86 gives a true representation. The spot indication of the instruments were connected on this diagram to facilitate comparison of the heights measured by the respective instruments.

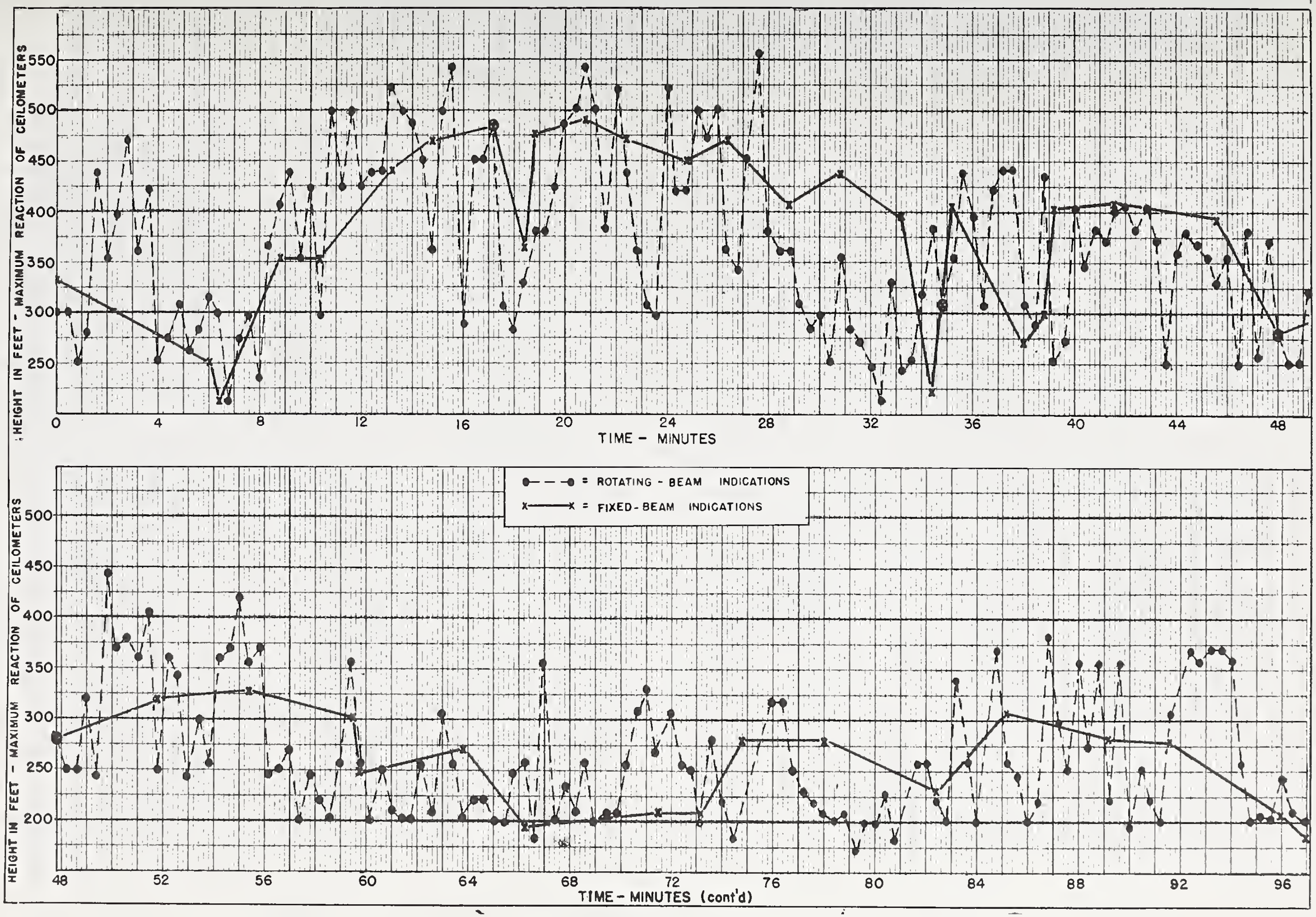

Figure 8.7 Comparison of rotating-beam and fixed-beam ceilometers [126].

Figure 8.8 is an expanded pictorial comparison of the two systems. The bottom picture shows possible undulations in the cloud base as it passes over the fixed-beam system during one cloud-height measurement. Most of the fluctuations are smoothed out and integrated into one measurement. During this time, the top picture shows the rotating-beam ceilometer making two discrete measurements. The horizontal extent of clouds passing during one indication of the rotating beam is represented by the separation in the detector cone-of-acceptance shafts shown between 0 and 1 second and 23 and 24 seconds.

Figure 8.9 is a pictorial comparison of the sampling rates and corresponding instrumental presentation of a rotating-beam ceilometer, which gives an indication every 24 seconds, and a fixed-beam ceilometer, which yields two indications every 12 minutes, both operating on a 438 foot baseline. The areas AA' and BB' represent the portions of the cloud base measured by the fixed-beam ceilometer. The drawing shows that the small-scale fluctuations in the cloud base are integrated into one indication of this instrument; while each indication of the rotating-beam instrument, represented by the black areas, includes only a small horizontal extent of a moving cloud.

The points of first reactions of the rotating-beam ceilometer refer to the lowest height at which a reaction occurs, and are represented by the bottoms of the "blips" shown on the oscilloscope presentations. The maximum reactions are represented by the widest portions of the traces, and the final reactions refer to the greatest height at which a reaction occurs, as represented by the tops of the "blips". A rate of one measurement every 24 seconds gives a rather complete base-contour picture, and leads to the belief that an instrument that will yield indications every six seconds will, for practical purposes, give a continuous cloud-base measurement.

In order to accurately describe the cloud base or ceiling, it is essential to know as much as possible about the variations or fluctuations in cloud base height that a pilot may expect to encounter during an approach. For this reason, the Weather Bureau changed their specifications for rotating-beam ceilometers in 1953 to require double-projector instruments rotating once every 12 seconds, which gives a cloud measurement every six seconds.

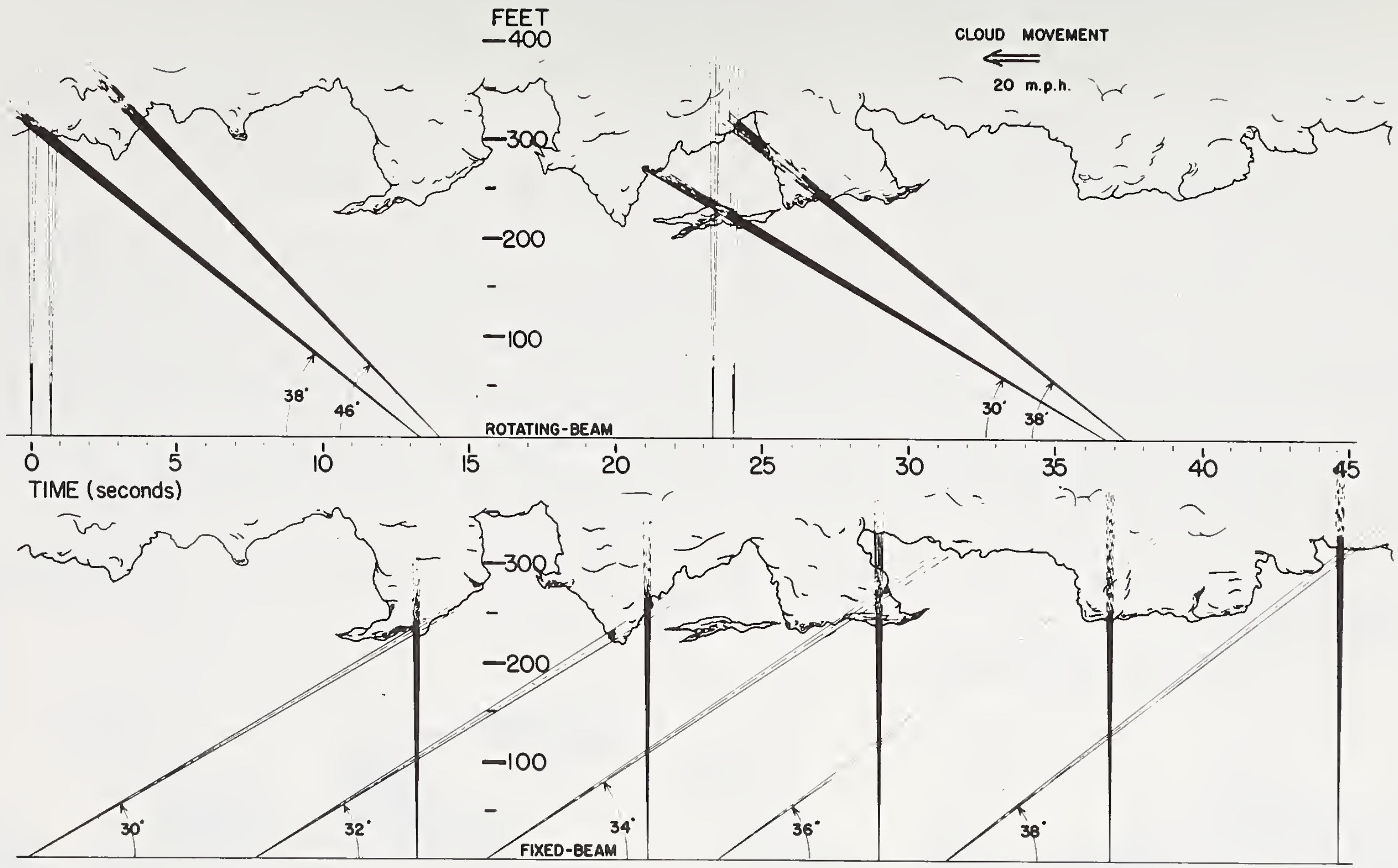

Figure 8.8 Pictorial comparison of ceilometers [125].

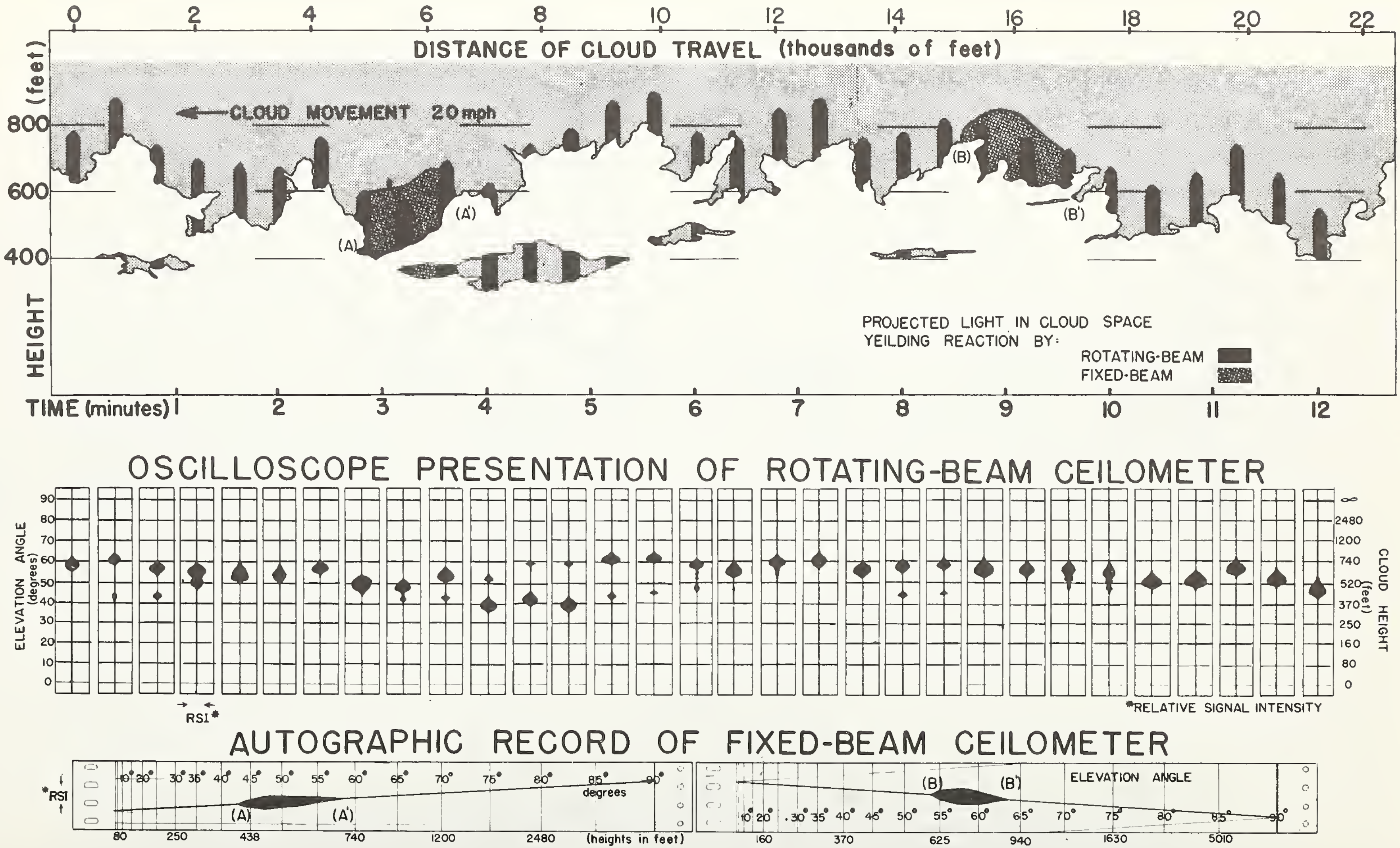

Figure 8.9 Sampling rates and corresponding instrumental presentations of rotating-beam and fixed-beam ceilometers [125].

8.6 FLASHTUBE PULSED-LIGHT CEILOMETERS

Early model pulsed-light ceilometers were also tested in the United States in the 1950's [125, 126]. The projector and detector are positioned side by side. A narrow beam of short (100 μ sec), intense pulses of light from the xenon source is directed at the cloud and a small portion is reflected back to the receiving equipment. The time interval required for each pulse of light to travel to and from the cloud is measured as an indication of range.

The results obtained with the pulsed-light ceilometer were discouraging. The intensity of the light and/or the sensitivity of the receiver was insufficient to allow cloud base measurements except in ideal atmospheric conditions. Moreover the length of the tail of the light pulse was so long that cloud heights below 500 feet could not be measured.

8.7 LASER PULSED-LIGHT CEILOMETERS

The laser beam ceilometers developed to date operate on the same time measuring principles as the pulsed-light ceilometer previously described. They are rangefinders, i.e., the time elapsed between the transmission of the laser pulse and the return of the laser energy scattered by the cloud is directly proportional to the cloud base height. Laser sources are capable of emitting pulses that are much shorter and more powerful than those of xenon sources.

8.7.1 Sperry Lidar Ceilometer

The National Weather Service conducted an evaluation of a Sperry lidar ceilometer (SLC) in 1973 [15, 38]. When possible, evaluations were made relative to the rotating beam ceilometer (RBC).

The projector of the SLC consists of a stack of 17 gallium arsenide (GaAs) diodes in a fiber coupled array. The projector emits 350 watt, 80 nanosecond pulses at 906 nanometers wavelength with a beam diameter of 10 inches (25 cm). This is much shorter than the 100 microsecond pulse length of the xenon pulsed-light ceilometer.

In comparison with an 800 ft baseline RBC, the relationship of SLC to RBC results was nearly linear. As SLC height changed 200 ft, the RBC changed about 300 ft. In evaluating the data, George stated there was no definitive method for determining which of the two ceilometers was more correct.

It should be pointed out that the response of the RBC can be interpreted many ways -- one does not have to necessarily use the point of maximum response, although maximum response has been the standard method.

In a sense, the SLC evaluation is consistent with the ANDB tethered ballon results [126]. Figure 8.10, both left and right, shows that the maximum reaction of both fixed and rotating-beam ceilometers is 200 feet when most highest visible balloon observation data plot around 300 feet. This is consistent with the 2/3 linear relationship between the SLC and RBC found by the National Weather Service. However, when first reaction of the RBC is compared with lowest partially obscured balloon observed, figure 8.11, very good agreement is obtained.

8.7.2 Erbium and Ruby Laser Ceilometers

Air Force Cambridge Research Laboratories recently reported on the results of the test and evaluation of two laser ceilometers in comparison with the RBC [98]. One was a ruby laser (694.3 nm) system manufactured by ASEA of Sweden and the other was a prototype "eye-safe" erbium laser (1.54 um) system developed by American Optical Company. Both ceilometers are high powered, single pulse systems. The 2 megawatt ruby laser pulse had a 30 nanosecond width. The 1 megawatt erbium laser had a 35 nanosecond pulse width.

Data comparisons showed that these lidars produced the same type of cloud height information as the RBC. They have a significantly greater ranging capability than the RBC and provide more cloud structure information. AFCRL concluded that lidars are potentially superior to the RBC as cloud-height measuring devices.

Additional comparisons between the ruby lidar ceilometer and the RBC

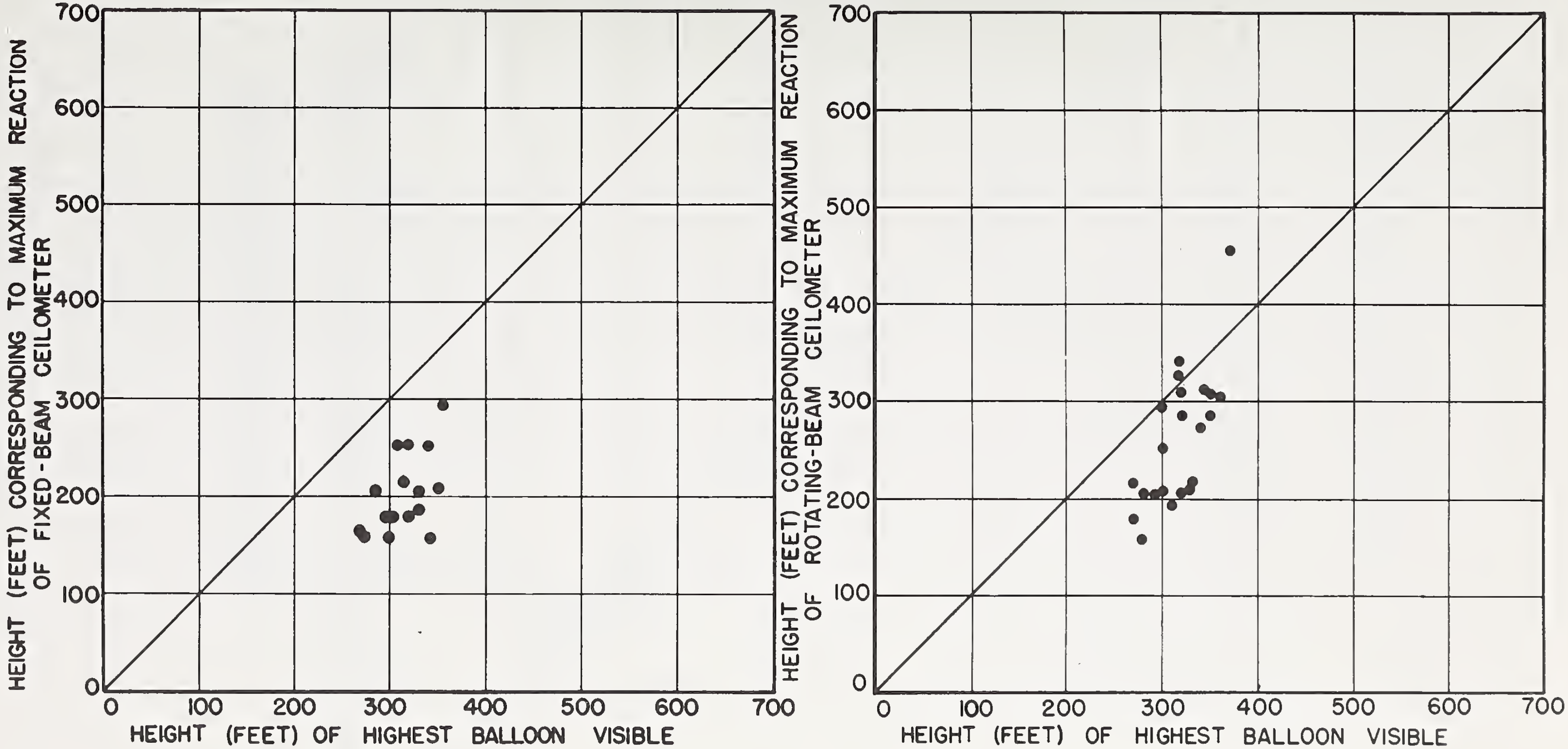

Figure 8.10. Comparisons of both fixed-beam and rotating beam ceilometers with highest visible tethered balloon [126].

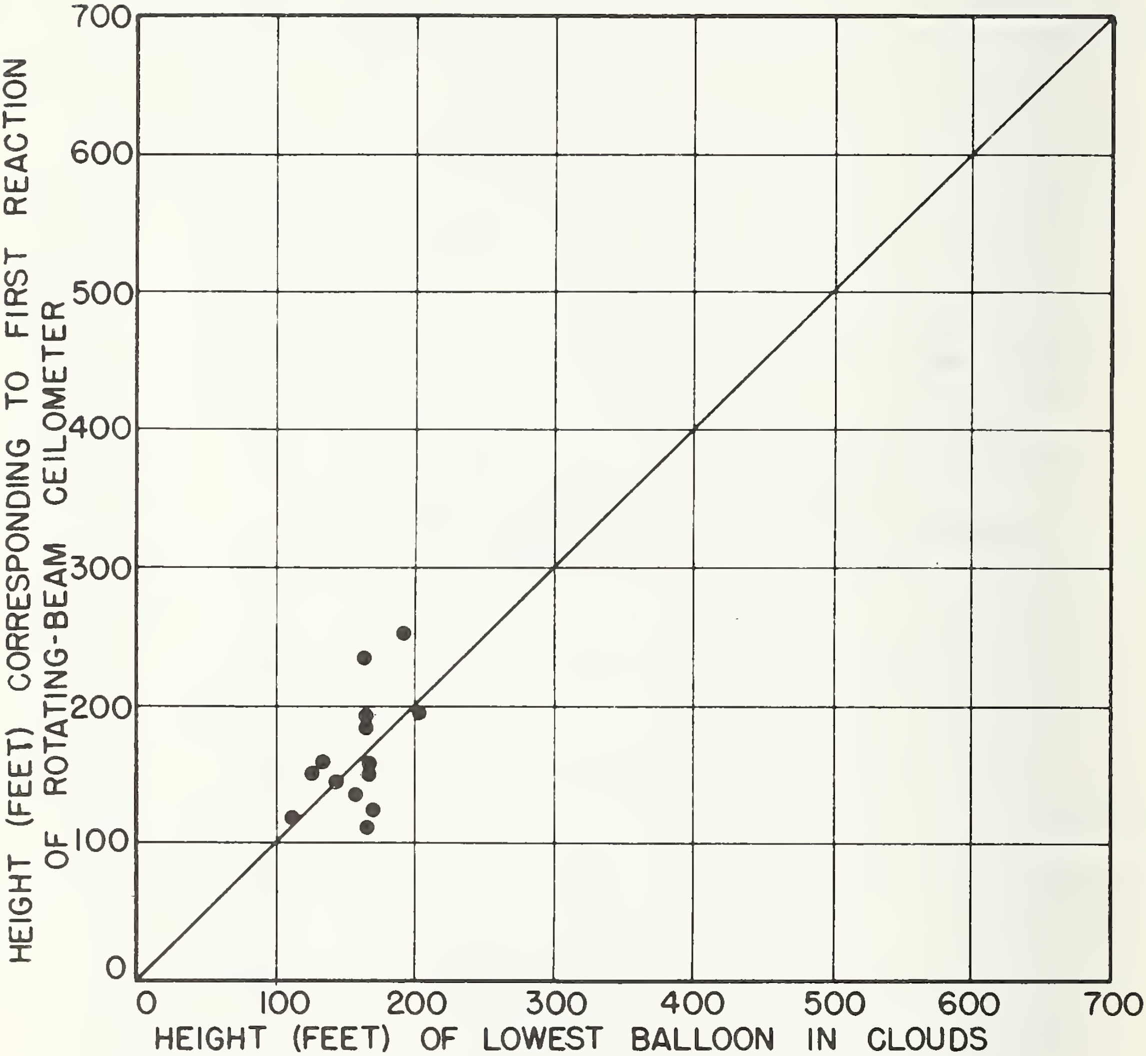

Figure 8.11 Comparison of rotating-beam ceilometer and lowest partially obscured balloon [126].

[99] show the lidar indicates an accurate presentation of cloud structure and that the RBC cloud return is affected by its geometry and by multiple scatter in the cloud. These effects bias the RBC to indicate somewhat higher cloud heights. However, the difference in cloud heights as measured by the two systems is not significant.

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APPENDIX A

Topical Outline of the First Weather Bureau
Meeting on Runway Visual Range
Washington, D. C.
May 5 & 6, 1949

I. Statement of Problem:

1. Requirements for Ceiling and Visibility Data for:

a. Civilian Aviation Operation
(by Representatives of CAA)

b. Military Aviation Operation
(by Representatives of the Military Services)

c. FIDO Operation
(by Representatives familiar with Landing Aids Experiment Station work)

2. Summary of Discussions of the Problem.

II. Plan of Attack:

1. Discussion of solution to problem by:

a. Employing ceilometer and transmissometer at selected points to give in effect glide path visibility.

b. Employing pulsed light range meter to obtain required information.

c. Employing 1 cm radar to obtain required information.

d. Other means.

a. To be discussed by person familiar with Landing Aids Experiments.

b. To be discussed by Signal Corps and Weather Bureau.

c. To be discussed by Signal Corps.

2. General discussion of proposed solutions.

III. Present Engineering Assignments having Bearing on Solution of Problem:

1. Outline of projects bearing on problem and being carried out by:

    a. Signal Corps

    b. Weather Bureau

    c. Other Agencies

2. Summary Discussion

IV. Future Plans:

1. Plans covering development and testing of equipment by:

    a. Weather Bureau

    b. Signal Corps

    c. Other Agencies

APPENDIX B

NOTES ON THE ABSORPTION OF LIGHT BY AIR AND THE RANGE OF DIFFERENT LIGHTS*

-France-

/Following is a translation of an article by a Staff Engineer, Central Lighthouse Service, in the French language periodical Archives, Visibilité des Feux (divers)(Archives, Visibility of Lights (Varied)), Paris, April 1860, 4 pages./

Light, in traversing any medium, is subjected to loss or partial absorption independently of intensity loss due to distance increase. The absorption effected by each infinitely thin surface cross section is evidently proportional to the density of this cross section and to the intensity of the light which traverses it, so that if we call y the luminous intensity and dx the density of a surface cross section, the loss due to absorption is expressed by

$$dy = -ky\, dx.$$

If the rays are divergent, the intensity will also diminish inversely as the square of the distance, and we then have:

$$\frac{y+dy}{y} = \left(\frac{x}{x+dx}\right)^2 = \left(1+\frac{dx}{x}\right)^{-2} = 1-2\frac{dx}{x}$$

and

$$dy = -2\frac{ydx}{x}.$$

The total attenuation of intensity is the sum of these two expressions so that we finally have a differential equation:

$$\frac{dy}{y} = -2\,\frac{dx}{x} - k\, dx\ ,$$

and we obtain

$$y = \frac{L\, a^x}{x^2}.$$

*An unsigned Note was sent to Douglas by Monsieur P. Blaise, of the French Lighthouse Service, who stated that the author "could be none other than Allard."

The quantity $a = e^{-k}$ varies from 0 to 1 depending on whether the medium absorbs completely or allows all the light to pass; this is the coefficient of transparence of the medium under consideration. L represents the intensity of the luminous source of light at unit distance in vacuum or for $a = 1$.

We will indicate the results that can be obtained by applying this formula to the passage of light in the atmosphere.

From experiments performed by Bouger and reported by Lacaille in his optics, it follows that a horizontal section of 189 fathoms or 368.4 feet of air causes a loss of one hundredth of the light and that 7469 fathoms, or 14,557.4 feet dissipates a third. Taking the kilometer as the unit of distance, we should therefore obtain: $0.99 = a^{0.3684}$ and $2/3 = a^{14.5574}$. The first of these equations gives $a = 0.9731$ and the second gives $a = 0.9725$. We can take $a = 0.973$ as representing the coefficient of transparence of air during Bouger's experiments.

In order to determine the range of a light L, i.e. the farthest distance at which this light can be seen, it is necessary to define another coefficient λ which represents the smallest quantity of light perceptible to an observer. Thus:

$$\lambda = \frac{La^x}{x^2} .$$

This equation, solved with respect to x, will give the range of a light L in an atmosphere whose transparence is a, for an observer whose eye cannot perceive a luminous intensity smaller than λ . Only one observation is necessary to determine λ . Thus, for example, we have recognized at the lighthouse workshop that one pilot light representing 1/200 carcel could just be perceived when judged at 500 meters. If we assume that the transparence of the atmosphere during this observation was the same as that during Bouger's experiments - 0.973 - we will have:

$$\lambda = \frac{1/200(0.973)^{1/2}}{(1/2)^2} = 0.019728.$$

This value of λ should be checked by new experiments. If we accept it provisionally as valid, only the second equation

$$\frac{La}{x^2} = 0.019728$$

will be required to obtain the intensity L of the smallest light that could be perceived at a given distance x, or likewise the greatest distance x at which a given light L could be seen, in different atmospheres of transparence a. The results are given in the following Tables:

Distance x	Intensity L of the smallest light which can be perceived at distance x, when the atmosphere has a coefficient of transparence a =									
	1.00 vacuum	0.973 clear air	0.95	0.93	0.925	0.90	0.85	0.75	0.50	0.25
1	0.019	0.020	0.021	0.021	0.021	0.022	0.023	0.026	0.039	0.079
5	0.493	0.566	0.637	0.709	0.728	0.835	1.112	2.078	15.782	505.030
10	1.973	2.594	3.295	4.076	4.302	5.658	10.021	35.032	2020.1	505.030
15	4.479	6.692	9.581	13.183 (1)	14.290	21.553	50.802	332.088	145.450.0	
20	7.891	13.642	22.018		37.523	64.906	203.585	2488.3	"	33.688
25	12.33	24.46	44.45		86.58	171.75	716.95	16,384.7	"	75.664
30	17.76	40.36	82.72		184.10	418.83	2326.75	99,422.0		156.61
35	24.11	62.99	145.57		369.96	965.20	7136.0	572,500.0		306.42
40	31.56	94.34	245.61		713.70	2135.45	21010.0	"		575.28
50	49.32	193.10	640.96		2431.80	9569.2	166747.0			1857.25
60	71.02	366.50	1541.64		7636.0	39520.0	"			5525.9
70	96.67	656.72	3504.5		22668.5	154300.0				15530.0
80	126.26	1127.87	7643.2		64554.0	577910.0				41939.0
90	159.80	1876.7	16159.7		178154.0	"				109670.0
100	197.28	3046.5	33322.0		479630.0					279760.0
150	443.87	26935.6	97434.0		"					
200	789.12	188174.0	"							

Luminous Intensity L	Valuex x of the greatest distance at which light L can be perceived in an atmosphere whose coefficient of transparence is a =									
	1.00	0.973	0.95	0.93	0.925	0.90	0.85	0.75	0.50	0.25
1	7.12	6.48	6.08	5.75	5.67	5.33	4.78	4.00	2.62	1.78
5	15.9	13.2	11.8	10.8	10.5	9.6	8.2	6.3	4.0	2.4
10	22.5	17.5	15.3	13.7	13.3	12.0	10.0	7.5	4.5	2.9
14	26.6	21.8	16.9	15.3	14.0	13.1	10.9	8.2	4.9	3.1
90	67.5	39.4	30.7	20.2	25.3	21.3	16.4	12.0	6.6	4.1
280	119.1	55.1	41.0	34.3	32.7	27.3	21.5	14.4	7.8	4.5
600	174.4	68.2	49.0	49.4	38.4	31.8	24.0	15.7	8.6	5.1
5000	503.4	105.	75.0	59.0	55	44	33	21	10.7	6.2
20000	1006.9	136	93	72.0	69	54	40	26	12.3	7.1
00000	2251.4	175	153	89.0	84	66	46	31	14	8.0

These tables allow us to appreciate the effect of atmospheric state on the range of lights. This effect is all the more stronger the more intense the light.

Thus, a mist which reduces the usual range of a carcel in clear air by 1/4 will reduce the range of a fourth order light by half, that of a second order light by 3/5 and that of a first order light by nearly 2/3. Likewise, if we compare two lights placed successively in different atmospheres, we see that the ratio of their ranges diminishes as the air becomes less transparent. For example, if a fixed first order light were replaced by an electric light 8 to 9 times stronger, 5000 burners to 600 burners, the range would be increased by half in ordinary air, by 1/4, 1/5 and even less in less transparent atmospheres.

The distances taken by navigators as representing the ranges of different lighthouses should be calculated on the basis of an atmosphere which is neither too clear nor too misty. We are using numbers which pretty nearly correspond to the coefficient a = 0.93. Here, moreover, are the ranges of different lights for this coefficient and for two similar ones 0.90 and 0.95, expressed in miles from 1852 meters. We also indicate the ranges which an electric lighthouse of 5000 burners will have.

Designations of lights	Intensity	Range, calculated in miles according to formula for a			Accepted range
		0.95	0.93	0.90	
Lamp burning 40 g (carcel lamp)	1	3.3	3.1	2.9	3
Fourth order light	14	9.1	8.3	7.1	10
Third order light	90	16.6	14.2	11.5	15
Second order light	280	22.1	18.5	14.8	18
First order light	600	26.4	21.8	17.2	20
Electric lamp	5000	40.5	31.9	23.7	11

If we want to adjust the numbers for the ranges so that they exactly correspond to identical atmospheric states, it would be necessary to decrease those of fourth and third orders a little and increase those of second and first orders a little. We could adopt either the numbers 8, 14, 18, 21, neglecting fractions, or 9, 15, 19, 22 using the next higher whole number. Under the same circumstances, the range of a first order electric light would be 31 or 32 miles.

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APPENDIX C

Nomographs for Computing the Visual Range of Lights

1.1 Allard's Law

$$E = IT^{D}/D^{2} \qquad (1)$$

can not be solved directly for D and can not be solved for I or T with an ordinary desk calculator unless logarithms are used. For these reasons nomographs are very useful in visual range computations. Such nomographs have been prepared in many different forms. Most of these nomographs lack flexibility in application in that they are based upon particular thresholds and units of distance. The nomographs used at the National Bureau of Standards for many years are shown in figures C-1, C-2, and C-3. They are based on a design developed by the late M. K. Laufer, and provide the desired flexibility.

The basic nomogram is an alignment diagram which can be used to solve equation (1) for one of the variables D, T, or I/E if the other two are known.

These nomographs have been prepared with the ratio I/E as one of the three variables. Hence the nomographs are applicable for any value of E. Since the value of E is usually the product of an integer and a power of 10, the relation

$$I/E = K$$

can usually be solved mentally. Moreover, any convenient unit of distance may be used provided that E, D, and T are in consistent units.

Four nomographs have been prepared, instead of a single nomograph, in order to cover the desired range of distance and transmittance without unduly compressing the scales and compromising accuracy. Transmissivities down to 0.10 are covered by figure C-1; to 10^{-10} by C-2; to 10^{-100} by C-3 (case III) and to 10^{-1000} by C-3 (case IV).

Auxiliary scales have been drawn to the right of the basic alignment diagram for easy conversion between transmissivity and related quantities. The defining equation is given for each scale. The DAY and NIGHT visibility scales are those used in the United States to relate transmissometer measurements to human visibility observations (except that the WMO contrast threshold of 0.05 have been used instead of the conventional 0.055. (See Section 5.5).

Example 1.

How far can a runway light with an intensity of 50,000 candelas be seen in daylight when the meteorological visibility is 0.035 miles. Note: For daylight, E = 1000 lumens per square mile (1000 mile candles). The solution: From 0.035 on VISIBILITY, DAY, draw a horizontal line to TRANSMISSIVITY scale. Since 0.035 is on CASE III scale, the transmissivity is read on the CASE III TRANSMISSIVITY scale. Thus, $T = 10^{-37.1}$.

Since $I = 50{,}000$ and $E = 1000$,

$$I/E = 50.$$

From 50 on the I/E scale, draw a line to $T = 10^{-37.1}$. Read D on CASE III DISTANCE scale as 0.10 mile.

Example 2.

How far can the same light be seen at night.

The solution: In this case E is 2 lumens per square mile (2 mile candles), and I/E is 25,000. From 0.035 on the VISIBILITY, NIGHT scale, draw a horizontal line to the TRANSMISSIVITY SCALE obtaining a T of 10^{-112}. Draw a line from this point to I/E = 25,000, obtaining a D of 0.06 mile. Note that the CASE IV scales are used.

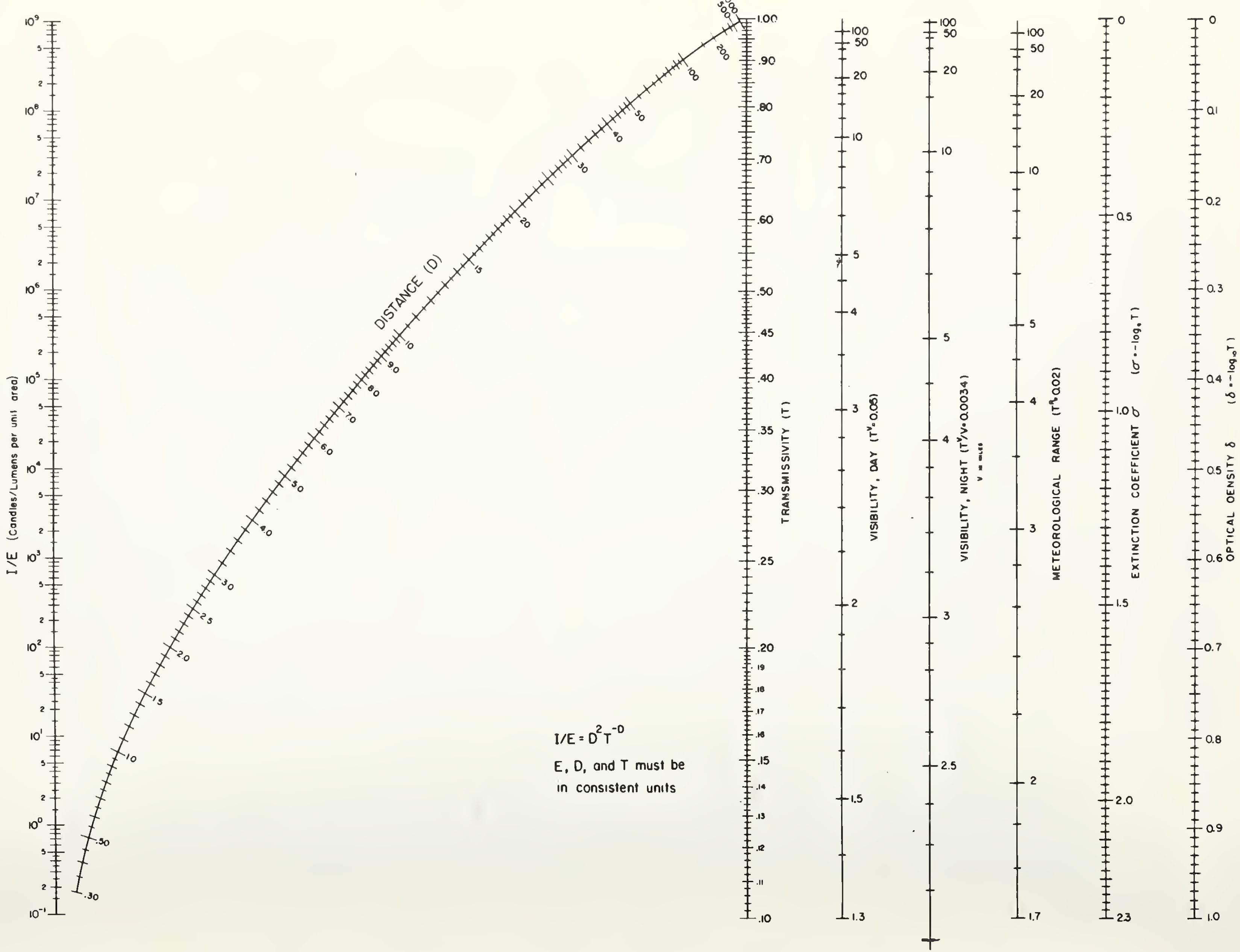

Figure C-1 Generalized nomograph for the solution of Allard's law for distances in the range 0.30 to 500. E, D, and T must be in consistent units.

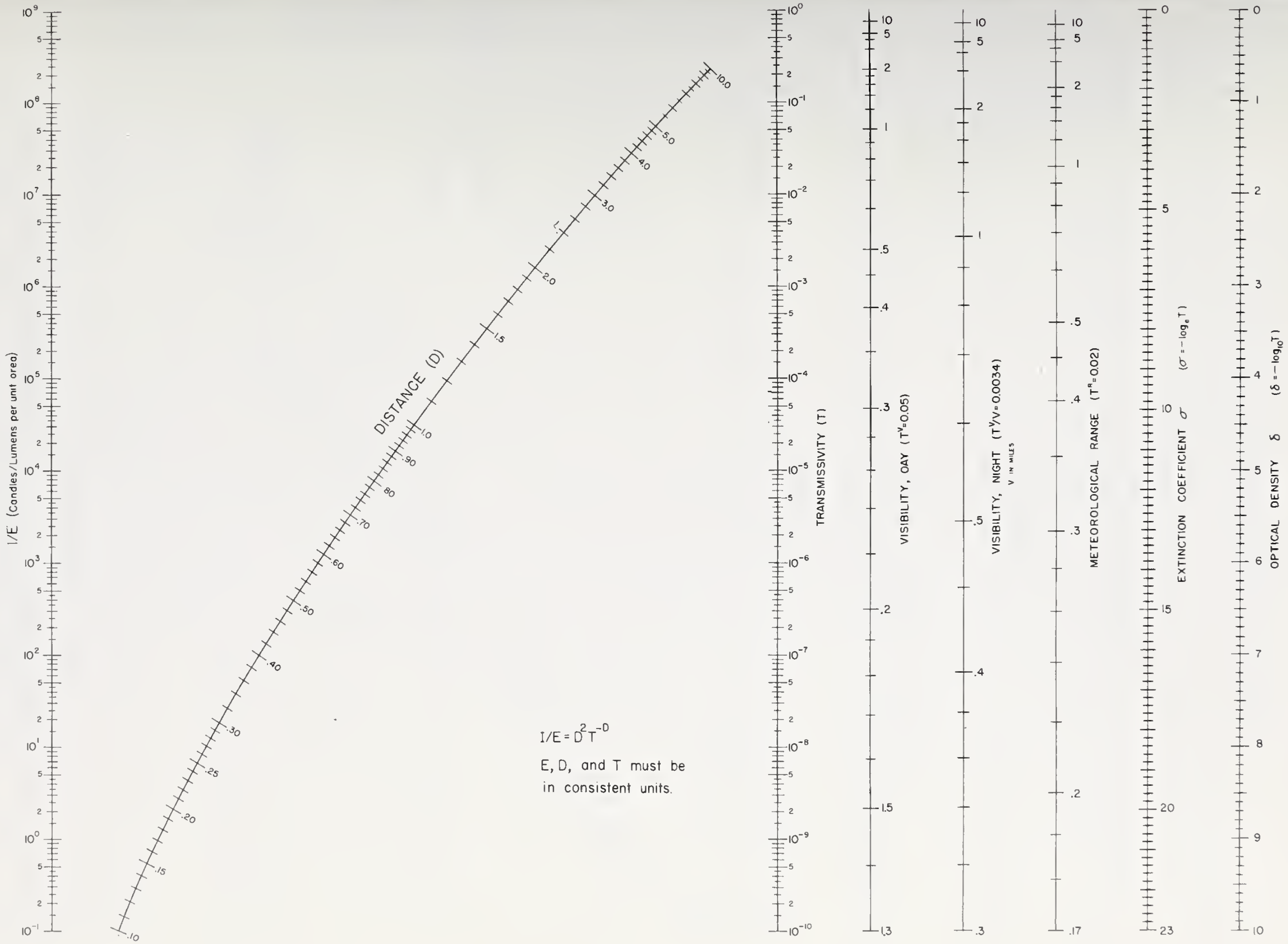

Figure C-2 Generalized nomograph for the solution of Allard's law for distances in the range 0.10 to 10.0. E, D, and T must be in consistent units.

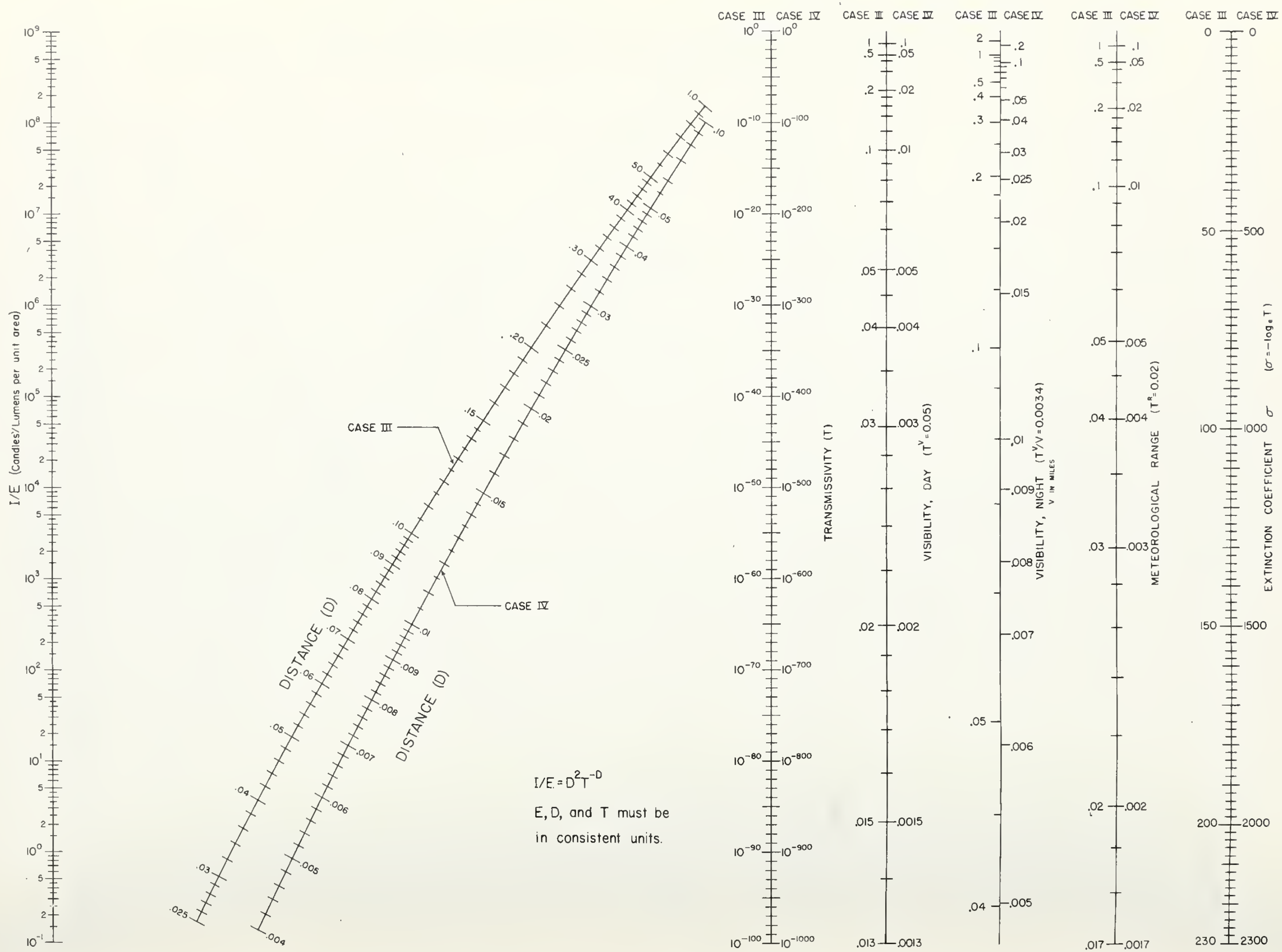

Figure C-3 Generalized nomograph for the solution of Allard's law for distances in the range 0.004 to 1.0. E, D, and T must be in consistent units.

Appendix D

NBS Transmissometer Performance Check List
(Extracted from Reference [103].)

D-1 The following are the minimum performance requirements for a transmissometer properly adjusted and operating. The paragraph references indicate the paragraphs describing the corrective procedures.

D-2 PROJECTOR

Hourly Cutoff		Duration 45 to 75 seconds.
Manual Cutoff		Background switch to TEST turns off lamp.
Alignment		All small changes in alignment produce either no change or a decrease in the transmissometer reading.
Stability		No systematic changes in reading after lamp cutoff are observable.

D-3 RECEIVER

Alignment		All small changes in alignment produce either no change or a decrease in the transmissometer reading.
Stability of Pulse Rate		Width of the line of the clear-weather trace on the recorder does not exceed one chart division.
Minimum Pulse Rate	a.	With receiver lens blocked, pulse rate is not faster than one pulse in thirty seconds.

	b.	As the light falling on the receiver is decreased, the receiver will not stop pulsing until the pulse rate becomes slower than a pulse in thirty seconds.
Calibration		With the CALIBRATOR Switch ON, the TRANSMISSION meter reading differs from the CALIBRATION SETTING reading by not more than 1%.
Background		The pulse rate with the light off is less than 1 per second.

D-4 <u>INDICATOR</u>

Zero Adjustment	a.	With POWER switch OFF the TRANSMISSION meter and the recorder read zero.
	b.	The electrical zero of the indicator is within ± 1% of zero.
Calibration		With the CALIBRATE switch to TEST, the TRANSMISSION meter and the recorder differ from the indication of the CALIBRATION SETTING meter by not more than ± 1% for both positions of the RANGE switch.
Volume and Bias		Connecting a load of 0.1 megohm across the OUTPUT TEST jack causes no change in meter reading when CALIBRATE switch is in either position.
Meters		TRANSMISSION meter reading at the indicator and recorder reading differ by not more than 1%.

Stability	Zero and calibration settings do not drift more than ± 2% in 24 hours.
Chart Time	The gain or loss of time in the chart drive does not exceed one minute per day.

D-5 SYSTEM

Signal Line	Connecting a load of 1000 ohms across the INPUT TEST jack of the indicator causes no change in the meter reading.
100% Setting	On a clear day, the 100%-setting factor differs from 1.00 by not more than ± 0.03.
Stability	100% setting does not change more than 3% per week.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS MN 159	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Visual Range: Concepts, Instrumental Determination, and Aviation Applications			5. Publication Date June 1977 6. Performing Organization Code
7. AUTHOR(S) C. A. Douglas and R. L. Booker			8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* Federal Aviation Administration Systems Research and Development Service Weather Data Section Washington, D. C. 20553			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 77-7343

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This document is a review of the principles, procedures, and instruments used in the measurement of visual range. The fundamental concepts of the visual range of objects and lights are discussed. The principles of operation of the several classes of atmospheric attenuation meters are reviewed and representative instruments are described. The course of development of the NBS transmissometer, its validation and application to aviation operations is reported. An error analysis is made of the effects of instrument errors and of differences in observer thresholds on visibility measurements. A chronological review of the development and application of the runway visual range concept is included together with a discussion of cloud height measurements.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Ceilometer; runway visual range; scattering; transmissometer; visibility; visual range.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[X] Unlimited [ ] For Official Distribution. Do Not Release to NTIS	UNCLASSIFIED	362
[X] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13.44:159 [ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price

USCOMM-DC 29042-P74

☆ U.S. GOVERNMENT PRINTING OFFICE : 1977--240-848/178

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