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DEVELOPMENT OF A TRANSMISSOMETER FOR DETERMINING VISUAL RANGE

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CONTENTS

TABLE INDEX

FIGURE INDEX

CA INFORMATION AND STATISTICS

DEVELOPMENT OF A TRANSMISSOMETER FOR DETERMINING VISUAL RANGE

SUMMARY

This report presents a discussion of the problem of determining visual range from measurements of the transmission of the atmosphere between two fixed points, a description of the development of an instrument for measuring atmospheric transmission, and a study of the correlation between the measurements of transmission obtained with this instrument and the prevailing visual range It was found that the correlation between the transmission measurements and the visual range of non-luminous objects by day followed the theory developed by Koschmieder, whereas that between transmission measurements and the visual range of lights at night showed systematic deviations from Allard's law which has been generally accepted for use in determining visual ranges of lights The development of this equipment was initiated and financed by the Civil Aeronautics Administration, Technical Development Division

INTRODUCTION

When a prospective pilot is given a physical examination, or when he undergoes his periodic physical checkup, the eyesight is carefully checked Vision is of the utmost importance in aviation, particularly distant vision It is of importance to a pilot scanning the skies ahead of him and the landscape below, and to the control tower operator in directing the aircraft within his area For this reason, any factor affecting vision or restricting distant vision is of immediate importance The transmissivity of the atmosphere is one such factor, and a very important one, as it directly affects the distance at which objects and lights can be seen This suggests that a transmissometer for measuring this property would be useful in determining visual ranges for the airway and airport services A transmissometer might also be used for the control of luminous aids to air navigation For example, the effective use of high intensity approach lights requires a knowledge of the transmission or visual range in order that a satisfactory adjustment of the lights may be made

At locations where no visual range observations are being made because of the absence of observers, or because of the lack of visibility marks at suitable distances, a transmissometer could furnish, at least in part, a desired indication of the visual range Furthermore, it has been proposed by several writers that a transmissometer might give more precise and dependable results than can be obtained by visual observations. If this is the case, and if such measurements could be made continuously, an earlier indication and resultant warning of changes in visual range would result For synoptic meteorology the transmission measurements themselves might be used as an aid in identifying air masses

These considerations seemed to warrant the development of a transmissometer and, through the National Bureau of Standards, the Technical Development Division of the Civil Aeronautics Administration undertook the development This report describes the results of this project, the instrument developed, and the results obtained with it

There are several possible types of transmissometers [1] The type selected for development utilizes a photoelectric receiver which measures the light falling upon it from a light source after the light has passed through the sample of atmosphere between the source and the receiver, as it is believed that this type is more precise and more easily used by untrained observers than the types requiring visual photometry. In this report the term transmissometer is used to mean an instrument of this type

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[1] A rather complete discussion of many types of transmissometers is given by W E K Middleton, "Visibility in Meteorology," 2nd Ed , Chap VII, 1941

DEFINITIONS

According to the definitions of the American Standards Association,[2] "The regular transmission factor of a body is the ratio of the regularly transmitted light to the incident light "

There is no A S A definition for transmissivity but, as generally understood, the transmissivity is the regular transmission factor per unit distance within a light transmitting medium

It is impracticable in the case of the atmosphere to measure a property which agrees exactly with the above definitions The simplest procedure is to consider the light received from the source through a very clear atmosphere as the incident light and the light received by the same equipment in any less clear atmosphere as the transmitted light The transmitted light will include some scattered light which, though radiated by the source, would not reach the receiver in clear weather The term "transmission" in this report will be used to define the ratio of the transmitted to the incident light as measured, while the term "transmissivity" will be used as defined above

An object is taken to be on the threshold or at the limit of visibility when it is seen just clearly enough so it can be identified A light is taken to be on the threshold or at the limit of visibility when its intensity is just sufficient for the light to be located and seen steadily

When an object or light is on the threshold, the distance between the object or light and the observer is called the visual range of that object or light In this report the term "visual range," when not referred to a particular object or light, is used to express what is usually called "visibility" by the meteorologist

In this report the term "threshold," when not used for the threshold of a particular observer, will be used as the value of the threshold of an average observer whose eyes are adapted to the prevailing illumination

FUNDAMENTAL REQUIREMENTS OF A TRANSMISSOMETER

From a consideration of the laws relating visual range and atmospheric transmission, the fundamental requirements of the components of a transmissometer may be determined The generally accepted laws relating visual range and transmissivity are

For black objects above the horizon during the daytime,

$$(B-b)/B = T^d \qquad (1)$$

where

B is the brightness of the background,
b is the apparent brightness of a black object of suitable size,
d is the distance from the observer to the object, and
T is the transmissivity of the intervening atmosphere

When $(B-b)/B$ is equal to ϵ_o (the contrast threshold of the observer), d is equal to the visual range of the object, D, so that

$$T^D = \epsilon_o \quad \text{(Koschmieder's Law)}^{3} \qquad (2)$$

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[2] "Illuminating Engineering Nomenclature and Photometric Standards," American Standards Association, Z7 1-1942, 30 115, issued by Illuminating Engineering Society

[3] Koschmieder, H , "Beitr Z Phys D Freien Atm ," 12 33-53 and 171-181, 1924

Note that in equation (2) the expression T^D is the transmission of the intervening atmosphere between the observer and the object and this is equal to the contrast-threshold of the observer

For lights at night,

$$E'/E = T^d \tag{3}$$

where

E is the illumination which would be produced by a source at a distance d if the intervening atmosphere were "ideally" clear, and

E' is the illumination produced by the source when the transmissivity is T

Since E is equal to I/d^2 where I is the intensity of the source, then

$$E' = IT^d/d^2 \tag{4}$$

When E' is equal to E_v (the illumination threshold of the observer), d is equal to the visual range of the light, D, so that

$$IT^D/D^2 = E_v \quad \text{(Allard's Law)} \tag{5}$$

It is essential to note that in both laws the 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 the receiver of a transmissometer The effect of small instrumental errors on the indicated visual range of objects by day may be found as follows

The transmissivity is given by

$$t^{1/R} = T \tag{6}$$

where

T is the transmissivity,
R is the distance, and
t is the transmission between the transmissometer light source and receiver

Substituting for T in equation (2)

$$\epsilon_o = t^{D/R} \tag{7}$$

If t_1 is the transmission indicated by the instrument, then D_1, the visual range determined from this transmission, is given by

$$\epsilon_o = t_1^{D_1/R} \tag{8}$$

If $\quad t_1 = (1+m)t$

and $\quad D_1 = (1+n)D$

where m is the relative error in the transmission measurement and n the relative error in the indicated visual range,

then $$t_1^{D_1/R} = \left\{(1+m)t\right\}^{(1+n)D/R} = t^{D/R} \tag{9}$$

and $$(1+n)\ (D/R)\ \left\{\log(1+m) + \log t\right\} = (D/R)\ \log t \tag{10}$$

since, from (7), $\log t \doteq (R/D) \log \epsilon_o$, it is possible to substitute in (10) and obtain

$$D \log (1+m)/(R \log \epsilon_o) = -n/(1+n) \tag{11}$$

If m is sufficiently small this may be written as

$$n/(1 + n) = -m\ D/(R \log_e \epsilon_0) \qquad (12)$$

and if n also is small it may be written as $n = -m\ D/(R \log_e \epsilon_0)$ (12a)

Hence, the relative 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 at once 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 m is small, or the distance R, between the source and the receiver, must be an appreciable fraction of D, the visual range However, an increase in R raises the minimum visual range which can be determined and requires a light source of higher intensity The effects of the separation of light source and receiver are illustrated in table I, where the permissible spreads of transmissometer indications (if errors in the indicated visual range are not to exceed 20 percent) are given for several distances between source and receiver The transmissivities corresponding to the visual ranges listed were computed by means of equation (2) using for ϵ_0 the generally accepted value, 0 02 The computations of the values limiting the permissible range of transmission measurements from the transmissivities are independent of the value of the contrast-threshold The assumption of different values of this threshold affects only the values of the visual ranges corresponding to these transmissions

From the table it is seen that, to obtain a reasonable precision in the determination of the higher visual ranges, either a very accurate instrument is required or the distance between the light source and receiver of a transmissometer should be large, whereas the corresponding distance must be small if a transmissometer having a practicable range of instrumental readings and a readily obtainable sensitivity is to measure low visual ranges Thus the minimum visual range to be measured by a given transmissometer determines the maximum separation of the source and the receiver But this maximum separation may be so small as to make the determination of high visual ranges very inaccurate From a consideration of this table alone it is evident that it is not feasible to design a transmissometer which is adapted to the measurement of all the atmospheric conditions that are of interest for different purposes

It must be emphasized that in the above discussion of errors a strictly homogeneous atmosphere has been assumed In practice, the relatively small sample of the atmosphere between the source and the receiver may not be representative of the atmosphere through which the visual range is desired, so the resulting measurement will be misleading to an extent depending upon the degree of non-homogeneity

If the distance between source and receiver is made large to obtain accuracy for large visual ranges, variations in temperature throughout the sample of atmosphere may cause refraction and "shimmer" of the rays of light from the source directed toward the receiver These refractive effects may cause a greater change in the reading of a transmissometer than in the actual visual range

The magnitude of the refractive effects depends upon the optical design of the transmissometer For the usual type of projectors and photometric receivers, a light source having a uniform intensity throughout a solid angle larger than that subtended by the aperture of the receiver (by an amount equal to the maximum bending of light rays) is required if the amount of light from the source falling on the aperture of the receiver is to be independent of the bending due to refraction along the path Likewise the angle of acceptance of the receiver must be sufficiently large if the readings are to be independent of changes in the direction of incidence due to refractive effects However, if the solid angle of acceptance of the receiver is such that light in directions other than that from the source is included, the readings will not be independent of background brightness. On the other hand, if the angle of acceptance is limited to that of the dimensions of the source, any slight change in alignment will decrease the amount of light received from the source and at the same time admit light to the receiver from the background The difficulty of the background brightness can be limited to a great extent by using a modulated light source

TABLE I

TRANSMISSION LIMITS FOR ERRORS IN VISUAL RANGE OF ± 20 PERCENT

Visual Range Kilometers	Transmissivity per km	R* = 0.1 km min	R* = 0.1 km max	R = 0.25 km min	R = 0.25 km max	R = 0.5 km min	R = 0.5 km max.	R = 1.0 km min.	R = 1.0 km max	R = 2.5 km min	R = 2.5 km max
50	0.92	0.99_0	0.99_3	0.97_6	0.98_4	0.95_2	0.96_8	0.91	0.94	0.78	0.85
25	0.86	0.98_1	0.98_7	0.95_2	0.96_8	0.91	0.94	0.82	0.88	0.61	0.72
10	0.68	0.95_2	0.96_8	0.88	0.92	0.78	0.85	0.61	0.72	0.29	0.44
5.0	0.46	0.91	0.94	0.78	0.85	0.61	0.72	0.38	0.52	0.09	0.20
2.5	0.21	0.82	0.88	0.61	0.72	0.38	0.52	0.14	0.27	0.008	0.04
1.0	0.020	0.61	0.72	0.29	0.44	0.09	0.20	0.008	0.04	$10^{-5.3}$	$10^{-3.5}$
0.50	0.0004	0.38	0.52	0.09	0.20	0.008	0.04	$10^{-4.2}$	$10^{-3.0}$	$10^{-10.6}$	$10^{-7.1}$
0.25	$10^{-6.8}$	0.14	0.27	0.008	0.04	$10^{-4.2}$	$10^{-3.0}$	$10^{-8.5}$	$10^{-5.7}$	10^{-21}	10^{-14}
0.10	$10^{-17.0}$	0.008	0.04	$10^{-5.3}$	$10^{-3.5}$	$10^{-10.6}$	$10^{-7.1}$	10^{-21}	10^{-14}	10^{-53}	10^{-35}
0.05	$10^{-34.0}$	$10^{-4.2}$	$10^{-3.0}$	$10^{-10.6}$	$10^{-7.1}$	10^{-21}	10^{-14}	10^{-42}	10^{-28}	10^{-106}	10^{-71}

*R = distance between transmissometer light-source and receiver and a receiver designed to respond only to light modulated at that frequency

The sensitivity of the receiver determines the minimum intensity of the light source that can be used In practice this may require some form of projector, although the beam of light from the usual projector does not satisfy the requirement of uniform intensity distribution By using a short focal length projector and a lamp with a high-current filament, or by using a reflector type projector with a spread lens, a beam of uniform intensity may be approximated Generally the beam spread of such a source will be so large that when the installation is at or near an airport, it may interfere with the vision of pilots If so, some means of screening the source will be desirable This can be accomplished by using diaphragms to confine the beam and a screen behind the receiver

Since the reading of the transmissometer is proportional to the light incident on the receiver, it is necessary that the intensity of light from the projector in the direction of the receiver be maintained constant, well within the limits of the accuracy to which the transmission is to be determined It is possible to design a type of transmissometer that diverts a portion of the light from the source so that it does not pass through the sample of atmosphere and to obtain a differential measurement between this light and that transmitted through the sample With such an instrument the necessity of a constant intensity source is obviated, but the complications introduced are likely to be greater than those required to obtain a reasonably constant source

Errors arising from the variations of the source and the receiver with respect to temperature, humidity, instrument drifts, and power supply must of course be less than the total permitted error Likewise, the transmission or reflection properties of all components of the optical system (lenses, reflectors, cover glasses and the like) must not change with time or with changes in weather conditions Consideration must be given to condensation of moisture internally or externally, salt spray, driving rain or snow, dust, frost, dew, insects, debris, and many other such items

The usefulness of a transmissometer depends to a large extent upon the manner in which the transmission or visual range is indicated Frequently the indication will be desired at a location remote from the transmissometer Hence a method of indication should be provided that will permit the relaying of readings without the introduction of additional circuit errors, or if errors are introduced the readings should be corrected When the same model of a transmissometer is to be used for various locations, an indication that can be transmitted without error would, of course, be desirable, so that special corrections need not be made for each instrument Likewise the method of taking readings should be sufficiently simple so that a special technique is not required

Among the possible means of transmitting the indication is the use of current, potential, and impulses Since the power available from photoelectric devices is limited, the leakages and attenuations of transmission lines may introduce serious errors in the indication by the output meter of a current or potential output from the receiver However, an indication by pulses based on the number per unit time rather than on the magnitude of the individual pulses can, in general, be transmitted without error Pulse counting may be done by several types of counters, which may be made recording if desired

DESCRIPTION

The transmissometer consists of a light source, a receiver, and an output meter, incorporating the following features, the choice of which was based on the preceding discussion

1 The light source is in the form of a projector having a uniform intensity of at least 100,000 candles throughout a solid angle sufficiently large so that small changes in the alignment of the light source will have no significant effect on the flux falling on the phototube of the receiver

2 The distance between the light source and the receiver was chosen so that transmissivities as low as 10^{-10} per kilometer can be indicated

3 The receiver was designed to give an indication in the form of pulses, the number of which is directly proportional to the light transmitted The receiver has an angular acceptance as small as practicable

4 The receiver and light source are designed for continuous operation and exposure to the weather

5 The output meter was designed to indicate the transmission directly at a location remote from the receiver

Figure 1 shows the general arrangement of the equipment The light source is a type-L lamp with a PAR-56 bulb having an internal parabolic reflector with an aperture of approximately 6 2 inches and a focal length of approximately 1 inch The filament is a single coil of type C-6, designed for 100 watts at 6 volts with a life of 500 hours The appearance of the lamp is similar to that of "sealed-beam" automobile headlight lamps, except that the cover is plain instead of prismatic The lamp operates at 5 1 volts, at which voltage the estimated life is 4,000 hours The lamp is mounted with the filament coil vertical so that the beam has a greater spread vertically than horizontally The short focal length of the reflector gives a relatively flat candle power distribution, as shown in figure 2

The optical system of the receiver consists of a lens, a diaphragm at the focal plane of the lens, and a phototube placed so as to receive the light which passes through an opening in the diaphragm The lens is a simple plano-convex spherical lens of 110-millimeter aperture and 710-millimeter focal length With the source at 250 meters from the lens, the image is a spot showing chromatic aberration contained within a circle 2 millimeters in diameter The opening in the diaphragm is 3 millimeters in diameter, which allows for a small alignment error Between the lens and the diaphragm is a set of baffles to reduce the stray light reaching the phototube from the walls of the housing

The phototube is of the RCA 929 type and is located as close to the diaphragm as practicable so that the cathode intercepts the entire cone of light from the image of the source The housing for the optical parts of the receiver and some of the parts of the photopulse circuit is a tube 4 5 inches in diameter This tube is provided with a cylindrical hood projecting 12 inches beyond the lens to provide some protection from driving rain and dust The reflector lamp is similarly protected with a 30-inch hood, which also serves as a baffle to reduce the stray light from the lamp

The general arrangement of the electrical equipment for the complete transmissometer is also shown in figure 1 The power supply for the receiver is located close to the unit in order to simplify the cable requirements The pulses are transmitted from the receiver to either or both of two types of indicators The length of the pulse transmission line can be changed for various installations without affecting the circuits

Power requirements are all 60-cycle, 110-volt About 100 watts is required for the source and 40 watts each for the receiver, the indicator, and the counter The power for the lamp is supplied by a 100-watt, constant-voltage transformer with a 115-volt primary and a 5-volt secondary The lamp and transformer are both contained in the same weather-tight housing

The circuit details of the phototube receiver and the pulse circuit are shown in figure 3 The electrical constants are given in table II The pulses are generated as follows The phototube current charges the capacitor C_1 until the voltage across it is sufficient to initiate a discharge through the neon lamp. The capacitor then rapidly discharges through the neon lamp and the resistor R_3 until the voltage across the neon lamp is no longer sufficient to maintain a current through the lamp. During the discharge the voltage drop across R_3 supplies a voltage pulse to the grid of the 6C5 tube which causes a momentary change in the plate current of this tube The resulting momentary change in voltage drop across R_6 (located in the power-supply unit) is the pulse signal that is transmitted to the indicator The time required to produce a given change in the voltage across the capacitor C_1 varies inversely as the current through the phototube

TABLE II

ELECTRICAL CONSTANTS OF TRANSMISSOMETER CIRCUITS

Receiver Circuit (Figure 3)			
Resistances		Capacitances	
1	0.1 megohm	1	0 0003 μf
2	25 ohms	2	0 0001 "
3	10,000 "	3	8 "
4.	20 megohms	4	0 05 "
5	150 ohms	5	8 "
6.	50,000 "		
7	5,000 "		
Indicator Circuit (Figure 4)			
Resistances		Capacitances	
1	0 1 megohm	1	0 0002 μf
2.	0 15 "	2	0 002 "
3	500 ohms	3	8
4	0 25 megohm	4	8 "
5	2,000 ohms	Inductance	
6	13,000 "		
7	2,000 "		
8	2,000 "	1	10 h
Counter Circuit (Figure 5)			
Resistances		Capacitances	
1	0 1 megohm	1	0 001 μf
2	1,000 ohms	2	4 "
3	50,000 "	3	4 "
4	20,000 "		
5.	10,000 "		

Therefore, the degree to which the pulse rate is proportional to the light incident on the phototube depends on the following factors (1) The degree of proportionality between the phototube current and the light flux incident upon its cathode, (2) the leakage currents across the components shunting C_1, (3) the constancy of the drop in voltage across C_1 for each discharge; and (4) the degree to which the time of discharging is negligible as compared to that of charging C_1

The characteristic of the type 929 phototube is such that, if the voltage across it is greater than 20 volts, the current is very nearly proportional to the incident light flux falling on the cathode The minimum phototube voltage is the difference between 105 volts (the voltage across tube VR-105) and the breakdown voltage of the neon lamp plus the drop across R_1 The maximum phototube current is less than 1 microampere, which gives a drop across R_1 of less than 0 1 volt Since the breakdown voltage of the neon lamp is about 80 volts, the minimum voltage across the phototube is about 25 volts A capacitor having high leakage resistance was used for C_1 and ceresin wax was used to insulate the component parts shunting this capacitor to further reduce the leakage currents. The total leakage current is less than 10^{-10} ampere The constancy of the drop in voltage across C_1 for each discharge depends upon the behavior of the neon lamp It was found that unless some light is incident on the neon lamp, its behavior is erratic The incandescent lamp shown in figure 3 provides the light needed The intensity of this light was adjusted to the minimum necessary for consistent operation of the neon lamp More light than this minimum increases the leakage current through the neon lamp when it is not discharging The minimum charging time used in the field was 0 02 second and the estimated time of discharge is of the order of 0 00001 second It is evident, therefore, that the departure from linearity should be small

Figure 4 shows the indicator circuit which gives a meter reading proportional to the input pulse rate, independent of the strength of the input pulses The electrical constants of this circuit are given in table II

An input pulse "triggers" tube 2050, which charges capacitor C_3 The charge on C_2 supplies part of the momentary current through this tube Capacitor C_2 is also necessary to quench the current through the tube As long as the strength of the input pulse is sufficient to trigger the tube, the charge flowing into C_3 per pulse is independent of the magnitude of the pulse When the pulse rate is constant, the voltage across C_3 assumes a constant value which is proportional to the number of pulses per second

The bridge circuit shown in figure 4 is essentially a vacuum-tube voltmeter giving an indication determined by the change in voltage across C_3 This bridge was designed to take advantage of the characteristic of voltage regulator tubes, namely, that the voltage drop across the tubes is substantially independent of the current through the tubes for considerable variations in current. The voltage drop from A to C is determined by the regulator tubes, VR-150 and VR-105, and the small voltage drop across R_3 As the resistance of the meter M is low, the voltage drop from A to B is substantially equal to that from A to C when S_1 is closed to a Thus the currents from A to B and from A to C must remain substantially constant. When a change in grid potential causes the plate current of the tube 6J5 to change, this change must be accompanied by a corresponding opposite change in the current through tube VR-105 while the voltage drops in the bridge are substantially unchanged The meter, therefore, measures the change in plate current of tube 6J5 produced by a change in grid potential As this change is a function of the change in voltage across C_3, it is determined by the pulse rate In practice R_5 is adjusted so that with no signal the meter reading is zero It is evident that the voltage drop across R_3 is independent of the distribution of current through the arms of the bridge Therefore, the grid bias of tube 6J5 is not affected by the plate current of the tube

This bridge circuit is preferable to the usual types of vacuum-tube voltmeters because the basic plate current of the metering tube may be balanced out, and because the plate voltage of the metering tube is very nearly independent of the plate current

In order that the relation between the voltage across C_3 and the change in current through the tube 6J5 be as nearly linear as possible the plate current of the tube is kept within the interval 3 to 9 milliamperes This current is made equal to 3 milliamperes for no input signal by adjusting the bias tap on R_3, using meter M with switch S_1 closed to b S_2 is a shunting switch used to reduce the current through the meter so that the range of the meter may be changed

For the field installation, the constants of the phototube circuit were adjusted to give a pulse rate of approximately 50 per second during the clearest weather and with the light source at a distance of 250 meters The resistor R_2 was adjusted so the increase in plate current was 6 milliamperes for a signal input of approximately 50 pulses per second

Figure 5 shows the circuit details of the pulse counter which was generally used for pulse rates of less than 5 per second Capacitor C_2 becomes charged to a potential of about 300 volts and discharges through tube 2050 and the counter N when the signal "triggers" the tube Quenching of the discharge is assured because of the inductance of the counter, together with the self-bias of the cathode due to the drop across R_2 The counter operates satisfactorily at frequencies as high as 10 pulses per second

PERFORMANCE OF THE INSTRUMENT

The performance of the transmissometer was tested both in the laboratory and during the field calibration which approximated service conditions

When the input voltage to the constant-voltage transformer which supplied the light source was in the interval 100 to 130 volts, the intensity of the source increased 0 1 percent per volt increase of input voltage It was found that with a constant illumination upon the phototube of the receiver, the response of the instrument increased 0 3 percent per degree C increase in ambient temperature for temperatures between -30° C and +50° C No changes due to high relative humidity were observed The response of the receiver was found to be linear to within the limits of measurement for illuminations over a range of 1,000 to 1 The reproducibility of the indications of the receiver was found to be approximately 3 percent

The transmissometer was operated continuously under field conditions for a period of 2-1/2 months There were no failures or replacements of any of the electronic or other parts of the instrument during this period

During this period of operation a gradual downward drift in the response of the instrument was observed This drift amounted to above 10 percent during the period of test Causes of this drift were traced to both the source and the receiver A slight blackening of the reflector of the source due to filament deterioration was observed It was found that there was a condensation of ceresin wax upon the inner surface of the lens of the receiver. It is probable that the characteristics of the various electronic elements also changed slightly with time The drift of the source can be reduced by operating the lamp at a lower voltage It is believed that a suitable thermoplastic can be used to replace the ceresin wax

Even with the protective hoods to protect the lenses of the receiver and the lamp, it was found that drying spots from rain would collect on these surfaces over a period of a few days The effect of these spots was found to be small, generally lowering the response by less than 3 percent

On occasion, driving rains or condensation covered the outer surface of the lens of the receiver sufficiently to reduce the reading of the instrument to less than half the reading with the lens cleaned It is believed that the effects of driving rain can be reduced by the use of more adequate hoods, and that the receiver including the lens can be kept at a temperature sufficiently high to materially reduce the chances of condensation forming on the lens

INSTALLATION FOR FIELD CALIBRATION

Koschmieder's law and Allard's law both involve threshold constants To use these laws to determine visual ranges from transmission data, a value of the contrast threshold or threshold illumination must be known Some values of these constants were available but these values are not consistent Furthermore, field tests were necessary in order that the reliability of the instrument could be studied A field calibration was therefore carried out in the summer of 1941

The development of high intensity approach-light systems required observations in fog, and Nantucket Island, Massachusetts was chosen as the location for that project It was decided, therefore, to calibrate the transmissometer at the same location so that the personnel and some of the equipment and observations could be applied to both projects The installation of the equipment was made about one-quarter mile from the south shore of the island near Surfside where periods of fog are frequent

Figure 6 is an aerial photograph of the locality The locations of the light source and receiver of the transmissometer, the visibility marks, and the area from which observations were made during periods of dense fog have been indicated Figure 7 shows photographs of the light source with its tubular hood mounted before it, the receiver and the visibility marks as seen from one of the observation points The auxiliary lamp shown below the hood of the source was not used

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 the photograph 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 candles The variation of the intensity of the lamps with horizontal angle was negligible

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 7 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-candle power light and a signaling lamp were located above the mark This mark was observed from additional observation stations outside the areas shown in figure 6 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

CALIBRATION PROCEDURE

The visibility marks and lights were observed from the area indicated in figure 6 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 the recorder in the control house the number of marks or lights that could be seen. The recorder 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 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 recorder 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 candles 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 on 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 illumination. In the reduction of the data the background reading was subtracted from the reading with the light on to obtain the true transmission 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 transmission. Since it was found that the clear weather readings decreased throughout the 10-week period during which the calibration data were taken, all data used were corrected for this drift of the 100 percent value.

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. A record of these Weather Bureau visibility observations was obtained through the courtesy of Mr. J. B. Underwood in charge of the Station.

RESULTS OF CALIBRATION

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 calibration curves. The data were rejected because the transmissometer reading or 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 III

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 visual-range observations have not been graded Weather Bureau data listing visual ranges less than the distance (2 5 miles) from the station to the test location were not used for calibration points

Figure 8 is a plot of the daytime calibration points for observations made on marks The visual range is plotted on a log scale and the transmission on a log-log scale. With these scales Koschmieder's law is represented by a family of straight lines with the contrast threshold, ϵ_0 , as a parameter, as is evident from equation (2)

TABLE III

DATA FROM WHICH ONE OF THE GRADE A POINTS WAS DETERMINED

Time	Transmission	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

This may be written $T^D = \epsilon_0$ (2)

$$\log(-\log T) = -\log D + \log(-\log \epsilon_0), \quad (13)$$

the terms $-\log T$ and $-\log \epsilon_0$ being used since both T and ϵ_0 are less than unity A plot of $\log(-\log T)$ against $\log D$ for this equation gives a straight line with a slope of -1 In the figure the ordinate scale has been inverted so that the transmission values increase with increasing ordinates

The value of $\log(-\log \epsilon_0)$ for the calibration curve was determined by obtaining the average value of $\log(-\log T) + \log D$ for the calibration points in figure 8 exclusive of the twilight and weather bureau points From this average value of $\log(-\log \epsilon_0)$, ϵ_0 was found to be equal to 0 055 This value is considerably greater than the value of 0 01 to 0 02 generally accepted The value 0 055, however, falls between the value 0 065 reported by Houghton[4] for clouds and his value for fogs which is about one-half that for clouds.

The line for ϵ_0 equal to 0 055 is a reasonable representation of the calibration points for the shorter visual ranges It may be 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 ϵ_0 = 0 031 and ϵ_0 = 0 098 were chosen so that for any given transmission 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 ϵ_0 = 0 234 and ϵ_0 = 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

To explain the apparent systematic departure of the calibration curve, ϵ_0 = 0 055, on the basis of a change in the contrast-threshold of the observer requires the assumption of a threshold for the longer visual ranges smaller than that obtained under ideal photometric conditions To explain it on the basis of an error in determining the transmissometer reading corresponding to 100 percent transmission would require the assumption that the 100 percent reading so chosen is higher than the true 100 percent reading Because of the method used in obtaining the 100 percent value, however, it is believed that the 100 percent point is not likely to be too high, though it might be too low Neither can this deviation be explained by assuming a somewhat non-linear response of the transmissometer, for the deviation is most marked in the region near the calibration point of the instrument This deviation may be explained, at least in part, by either of the following assumptions

1 The light falling on the transmissometer receiver was frequently reduced appreciably by refractive effects which did not affect the visibility of objects to the same degree that the transmission measurements were affected

2 The transmission of the sample of the atmosphere measured by the transmissometer was in most instances too low to be representative of the atmosphere in general on clear days, even though the atmosphere then appeared to be homogeneous

A classification of the calibration points according to the general illumination, as determined by the transmissometer background readings, showed no systematic differences of visual range with illumination This apparent independence of the visual range of objects with illumination is in agreement with previous investigations and theory Even the twilight points in figure 8 show no systematic differences Some of these points result from observations when it was so dark that the 25-candle lights

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[4]Houghton, J , "Journal of Aeronautical Sciences," Vol 6, pp 408-411

could be seen farther than the marks The computed average value of ϵ_0 for the twilight calibration points is 0 044 This value of ϵ_0 is less than that for the daytime value (0 055), whereas Nutting's results[5] show ϵ_0 increasing at low illuminations Because of the spread of the values for the comparatively small number of twilight points, however, the difference between ϵ_0 for daylight and ϵ_0 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[6] 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

Figure 9 is a plot of the calibration points obtained from observations on 25-candle lights The scales and symbols are similar to those on figure 8 In figure 9 are shown curves determined by each of the following relations

$$E_V = IT^D / D^2 \qquad \text{(Allard's Law)} \qquad (5)$$

$$S_V = IT^D / D \qquad (14)$$

$$I_V = IT^D \qquad (15)$$

Where I = 25 candles, and E_V, S_V, and I_V have been set numerically equal to 0 052, E_V has the dimensions of illumination and is expressed in kilometer candles, S_V has the dimensions of intensity per unit distance and is expressed in candles per kilometer, I_V has the dimensions of intensity and is expressed in candles

Although Allard's law has been generally accepted for determining the visual range of point sources, it has been suggested to the authors that equation (15) might be used in place of Allard's law. This law for I_V/I constant, like Koschmieder's law, is represented by a straight line Hence, it was decided to obtain the value of I_V/I from the nighttime grade A, B, and C calibration points in the same manner as ϵ_0 was obtained for the daytime calibration curve For I = 25 candles, this gave $I_V = 0\ 052$ candles The corresponding line is the one shown in the figure Equation (14) is an empirical equation proposed by the authors The curves for Allard's law (5) and equation (14) are based on the same numerical values of I and the threshold constant as were used in equation (15)

From the figure it is seen that the curve $S_V = IT^D/D$ gives the best fit for the calibration points obtained from night observations on the 25-candle lights It was found that this same relation also gave a better fit than either Allard's law or equation (15) for observations made at Nantucket in 1940 on a threshold lamp by two observers at different distances

It should not be inferred from this statement that the illumination at a point is not given by $E = \frac{IT^D}{D^2}$ but rather that the minimum perceptible illumination is not a constant and is such a function of T and D that $S_V = \frac{IT^D}{D}$ represents the data more satisfactorily. From this data it appears that the threshold illumination varies inversely as D, the visual range [7] Hence, if E_V is equal to $\frac{E_0}{D}$ where E_0 is the threshold

[5] Nutting, P G , "Transactions of the Illuminating Engineering Society," Vol 11, page 944, 1916

[6] Middleton, W E K , "Visibility in Meteorology," 2nd Ed p 92, 1941

[7] The variation of the threshold illumination will be discussed in a later report

illumination at unit distance, and is set at 0 052 where D is expressed in kilometers, equation (5) is then equivalent to equation (14)

It is seen that the curve $I_v = IT^D$ is not the most satisfactory straight line that could be drawn to represent the A, B, and C calibration points, although I_v has been adjusted to make the average deviation of these points from the line a minimum The slope of the line is not great enough However, changing the slope of the line requires not a change in I_v but a change in the exponent of T The required exponent is of the form D^k where k is some value greater than unity

In figure 10 the calibration points obtained from Weather Bureau observations and from observations on miscellaneous lights are shown in addition to those obtained from the observations on the 25-candle lights The twilight calibration points are also shown in this figure It is apparent that the curve representing Allard's law gives the poorest fit for the calibration points Changing the value of E_v would result chiefly in a translation of the curve Thus, the value of E_v could be increased until the Allard's law curve fits approximately the points at the low visual ranges, but the deviations at the larger visual ranges would be increased Moreover, even at the low visual ranges, the slope of the Allard's law curve would be somewhat too great

Although the straight line $I_v = IT^D$, $I = 25$ candles, fits the calibration points with the Weather Bureau and miscellaneous observations included better than either of the other curves, little significance can be attached to this fact As the intensities of the more distant lights used for Weather Bureau observations were considerably greater than 25 candles, the visual ranges obtained by observations on these lights should be greater Therefore, the calibration points obtained from these observations ought to lie below a calibration curve based on an intensity of 25 candles The deviation from the curve $S_v = IT^D/D$, $I = 25$, may, therefore, be explained on this basis as the intensities required to produce these deviations are of the order of the intensities of the lights which were used as marks In addition, there may be a systematic sampling error at night as well as during the day

In obtaining a transmissometer 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 limit of visibility at night when the transmissivity is such that an object at this distance would be at the limit of visibility by day If a transmissometer were calibrated by means of a system of such lights, the 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 ranges 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 transmission is such that object visibility by day is 1 kilometer or less, the visual range of a 25-candle light by night is about twice this distance This is evident from a comparison of figures 8 and 9 It seems preferable, therefore, that in practice nighttime visual ranges should be determined from a calibration curve which is based on lights having intensities comparable to those usually used as landmarks Twenty-five candles is about the minimum intensity of such lights Frequently lights of greater intensity are used, especially for the larger visual ranges The calibration curve to be used to determine visibility at night therefore should be based upon the intensity of the lights which the pilot uses and is expected to see from various distances

In figure 10 it is evident that the visual range of the 25-candle 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 calibration curve for marks, figure 8, agrees approximately with the determination of the visual range of these lights during twilight, in addition to giving a satisfactory determination of the visual range of objects

LIMITATIONS OF THE TRANSMISSOMETER

It is evident from the spread of the points shown on the calibration curves that there are limitations in the use of the transmissometer due to the instrumental errors and to the physical conditions under which the instrument must operate The estimated uncertainties in transmission measurements due to instrumental errors are summarized in table IV

TABLE IV

ESTIMATED UNCERTAINTIES IN TRANSMISSION MEASUREMENTS

1	Inconstancy of source	±1 percent
2	Variation due to ambient temperature	±2 percent
3	Uncertainty of indication	±3 percent
4	Uncertainty of "100 percent" value	±2 percent
5	Effects of atmospheric refraction	±2 percent
	Estimated uncertainty	±4 7 percent
	Expected average error	±1.2 percent

The error due to variation of the intensity of the source resulting from fluctuations of line voltage assumes a maximum variation in voltage of ± 10 volts The error due to variation in ambient temperature assumes a temperature range of ±7° C (± 13° F) The error arising from uncertainty of indication is based on the reproducibility of the instrument as observed in the laboratory The uncertainty of the 100 percent value is based on the consistency of the data taken on clear days to determine this value The only indication of the magnitude of the refractive effects was the degree of unsteadiness of the transmissometer readings when these effects appeared to be at a maximum

The estimated uncertainty was obtained by taking the square root of the sum of the squares of the individual uncertainties As it is believed that each of these uncertainties was not exceeded more than once per hundred observations, the expected average error has been computed on this basis

Using the values for the expected average error and estimated uncertainties given in table IV, it is possible to compute by means of equation (12a) the minimum visual range the transmissometer may be expected to indicate with any desired accuracy Using the value of the expected average error, 1 2 percent, it is found that when the visual range is more than 10 kilometers the expected average error in the indicated visual range due to instrumental inaccuracies exceeds 20 percent Similarly, using the value of the estimated uncertainty, 4 7 percent, it is found that when the visual range is 2 6 kilometers or less the discrepancy in the indicated visual range due to instrumental errors should never exceed 20 percent

It is also seen that for a visual range of 400 meters, T_{250} need not be determined to closer than -30 percent or + 40 percent for an accuracy of ± 20 percent in the visual range determination In this region errors in the visual range determinations resulting from inaccuracies in the transmission measurements due to instrumental errors are negligible

The spread of the calibration points is greater than can be explained on the basis of instrumental errors alone This is especially true of the points at the lower visual ranges Neither can these large spreads be explained on the basis of variations in the thresholds of the observers It is believed that these large spreads are due chiefly to nonrepresentative sampling As an example of the possible discrepancies due to nonrepresentative sampling, table V gives values of the visual range determined from the calibration curves of the transmissometer and the corresponding visual ranges determined by an observer from a point near the transmissometer These data, although taken for calibration points, were noted at the time as having some element of uncertainty in the sampling and were subsequently rejected as being nonrepresentative

TABLE V

EXAMPLES OF REJECTED DATA

Discrepancies Caused by Nonrepresentative Sampling	
Visual Range from Transmissometer	Visual Range from Observation
Kilometers	Kilometers
1 6	5
2 2	0 8
4	9
10	5

During the observations on the 25-candle lights it was frequently noted that there was a difference in the visibility of the light on the large target 30 feet above the ground and the lights on the small targets 10 feet above the ground This difference was observed from distances as great as 3 5 kilometers with differences in the angular elevation of only 0 1° It is evident that when the change of transmissivity with height is this large, the sample of atmosphere between the source and the receiver is not likely to be representative of the atmosphere through which marks are observed

In considering the spread of the calibration points for visual ranges of a kilometer or less, it should be remembered that the distance between the source and the receiver is an appreciable fraction of the distance between the observer and the mark at the visual range and that the line of observation was near and almost parallel to the line between the source and the receiver with only a small difference in height Even under these conditions there still were large discrepancies between the observed and the indicated visual ranges

It is evident from the calibration curves, figures 8 and 10, that the average discrepancies between the observed and the indicated visual ranges become larger than 20 percent before the computed upper limit, 10 kilometers, is reached Instead, the upper limit of reliable indications is limited, apparently by the effects of nonrepresentative sampling, to between 2 5 and 5 kilometers Thus, if these data are typical, the maximum visual range which the transmissometer may be expected to indicate with a useful degree of accuracy is 10 times or, at the most, 20 times the distance between the light source and the receiver

In considering the effects of nonrepresentative sampling it should be remembered that calibration data were taken only when the atmosphere appeared to be stable and homogeneous Moreover, it should be remembered that about one-third of the data so taken were rejected because these data showed the atmosphere to be considerably more unsteady or nonhomogeneous than was apparent It must therefore be concluded that at least at the place of calibration the variations in transmissivity of the atmosphere from point to point and from minute to minute are considerably greater than has generally been expected It is thus evident that the value of the atmospheric transmissivity obtained over a limited range cannot always be safely extrapolated to the region in general and, conversely, that general observations of the visual range cannot always be relied upon to give the atmospheric transmissivity in a given locality

In addition to the instrumental errors discussed above, there are possibilities of error due to background illumination, uncorrected drift, and deposits on the covers of the source and the receiver While these conditions were largely eliminated during the calibration, under service conditions they could cause large errors in the indicated visual range, if adequate provision is not made for their elimination or correction

The error in transmission measurement due to background illumination is absolute, not relative During daylight the background correction to be applied to the transmission determination was frequently as great as 0 05 It is evident that background illumination may produce an appreciable increase in the indicated visual range unless compensation is made For high visual ranges this error is quite large For low visual ranges the error again becomes serious since the illumination received from the background may become large in comparison to that received from the source On one occasion during a daytime fog, it was found that of an uncorrected transmission determination of 0 11 the background illumination accounted for 0 10 In practice the effects of background may be reduced or eliminated by reading the transmissometer with the source off as was done at Nantucket, by altering the design of the instrument so that the angle of acceptance of the receiver is reduced considerably (which introduces other difficulties), or by designing a receiver which will correct automatically for the background

If the readings are not corrected for the drift of the source and other components of the transmissometer, large errors may be introduced in the visual ranges corresponding to the higher transmissions, say T_{250} greater than 0.80 The light source and the receiver must be inspected frequently for condensation, rain, salt spray, and dirt Such accumulations have been found to reduce the indicated transmission to less than one-half of the true transmission

The minimum visual-range determinations which can be made by the transmissometer are limited by the maximum sensitivity of the instrument The lowest transmissions for which calibration points are shown in figure 9 correspond very nearly to the lower limit of response for the instrument For lower transmissions the receiver did not receive enough light from the source to operate Still lower transmissions could be measured, however, if the distance between the source and the receiver were reduced

The limitations of the transmissometer as used at Nantucket may be summarized as follows

1 For visual ranges of between 0 2 and 1 kilometer, with stable and reasonably homogeneous atmospheric conditions, the visual range indicated by the transmissometer will be within ± 20 percent of the observed visual range For visual ranges below 0 1 kilometer by day and 0 2 kilometer by night the 250-meter separation between light source and receiver is too great

2 For visual ranges in the region from 1 to 10 kilometers, the uncertainty in the visual range determination becomes progressively greater as the visual range increases For visual ranges greater than 5 kilometers, the 250-meter separation is too small and determinations of the transmissometer are unreliable

3 During daylight hours a correction must be applied for the background illumination

4 When the atmosphere is not homogeneous, the visual range indicated by the transmissometer may be quite different from that found by direct observation

APPLICATION OF THE TRANSMISSOMETER

From the discussion of the limitations of the transmissometer, it is at once evident that the instrument as installed at Nantucket is not capable of replacing all visual observations The satisfactory determination of visual ranges in clear weather requires a considerably greater separation of the light source and the receiver as well as a source of greater intensity In addition, a greater degree of atmospheric homogeneity than that likely to be obtained is necessary The determination of visual ranges of less than 250 meters requires a smaller separation between the source and receiver Moreover, if there is a marked lack of homogeneity of the atmosphere, the transmissometer measurements may give a false picture of the over-all conditions An observer scanning the horizon should notice and report any large variations in visual range, together with their direction This information could not be obtained by a single transmissometer The use of an impracticable multiplicity of instruments located over a considerable area appears to be the only way to reduce the effects of nonrepresentative sampling and to detect non-homogeneities, such as fog and smoke banks, approaching storms, and the like

The transmissometer should be useful as a supplement to visual observations during periods of low visibility (less than 1 kilometer) In this region the effects of instrumental errors are small, the sampling error for the transmissometer will be about the same as that for an observer There is generally an insufficient number of marks for satisfactory determination of visual ranges Consequently, the precision of the determinations made with the instrument should be comparable to that of the visual determination

In many localities there is a lack of suitable marks This is especially true at night in remote localities where there are few if any lights suitable for observation This situation exists at airports during blackout conditions where the lights normally observed are extinguished As the estimation of visual range on dark nights at localities where there are very few observable lights is extremely difficult, if not impossible, the transmissometer may be useful in giving a measurement of visual range under these conditions

The instrument may also be useful at automatic weather stations and at localities where continuous record of the transmissivity is desired It should also be useful in determining the conditions at particular localities where a better knowledge of the transmissivity or visual range is required than can be determined by an observer stationed some distance away - for example, the determination of the visual range at a landing field in the river valley when the weather station is located on a hill some distance away

The transmissometer appears to be well suited for use in controlling high-intensity approach lights Here a knowledge of the transmissivity of the atmosphere in the region of the approach lights is required. Consequently, during periods of dense fog the sampling with an instrument located near the lights is more likely to be representative than that for an observer who may be a considerable distance from the lights Satisfactory adjustment of the intensity of the approach lights requires a knowledge of the transmissivity during these periods of dense fog In general, the determination of transmissivity from visual range observations when the visual range is less than 500 meters is unsatisfactory because of the lack of a sufficient number of suitable marks and because of the large changes in transmissivity corresponding to relatively small changes in visual range

Observations indicate that the relation between the optimum intensity of high-intensity approach-light systems and transmissivity is of the form

$$I\ T^{c} = k,$$

where I is the relative intensity of the lights, T is the prevailing transmissivity, and c and k are constants for the particular system The expected values of c, 0 1 to 0 3, are such that the uncertainty in the determination of the relative intensity, I, will be about equal to the uncertainty of the transmissometer indication As a large tolerance is permitted in the intensity setting, the inaccuracies in the transmissometer indication resulting from instrumental drifts, temperature, voltage variations, uncertainty of the 100 percent value, and the like are insignificant Moreover, as the accuracy of the intensity setting is a direct function of the accuracy of the transmissometer indication, not of the accuracy of the visual range determined from the indication, the transmissometer is as well suited for this function during periods of clear weather as during periods of low visual range

A separation of light source and receiver less than that used in the Nantucket tests may be required as in many cases measurements of transmissivities less than 10^{-12} per kilometer, the lower limit of the instrument as installed for field tests, will be required

CONCLUSIONS

A transmissometer has been developed which includes a remote indicator, making it practicable to locate the instrument at a distance from the location at which the indications are desired This instrument will measure the transmission of the sample of atmosphere between the source and the receiver with sufficient precision to determine visual ranges up to 5 kilometers with usable accuracy For greater visual ranges the possible instrumental errors make the indications progressively more unreliable. The instrumental errors can probably be somewhat reduced by further development work.

A field calibration of the instrument has been made It was found that for daylight use Koschmieder's law provided a satisfactory calibration curve The value of the contrast threshold was found to be 0.055, which is considerably larger than the generally accepted value of 0 01 to 0 02

For nighttime use it was found that the use in Allard's law of a fixed value for E_v did not provide a satisfactory representation of the calibration points The assumption that the threshold illumination is not constant but varies inversely with the visual range provides a satisfactory representation

Frequently, the sample of atmosphere between the source and the receiver was not representative of the surrounding atmosphere, and this caused large discrepancies between the visual range as determined by the transmissometer and that observed visually, especially when the visual range was large For the determination of general visual range this is a serious drawback and limits the application of the instrument for this purpose

For the observations used in this calibration, the precision of visual range determined by the transmissometer was in general less than that observed visually by trained observers and with satisfactory marks In view of this limitation and the difficulties introduced by nonrepresentative sampling, there appears at present to be little advantage, if any, in the use of a transmissometer to replace visual observations for the determination of general visual range where trained observers and satisfactory marks are available

There are other conditions, however, where the effects of nonrepresentative sampling are greatly reduced, or are of little importance These include the application of the transmissometer

1. To supplement the periodic visual observations by a continuous record
2. To record the variations and rate of change of conditions of visual range, particularly under low visibility conditions
3. To replace visual observations where trained observers or satisfactory marks are not available
4. To provide a more accurate indication of visual range over a restricted area remote from an observer, particularly an approach zone
5. To provide accurate indications of visual ranges when visibility becomes poor

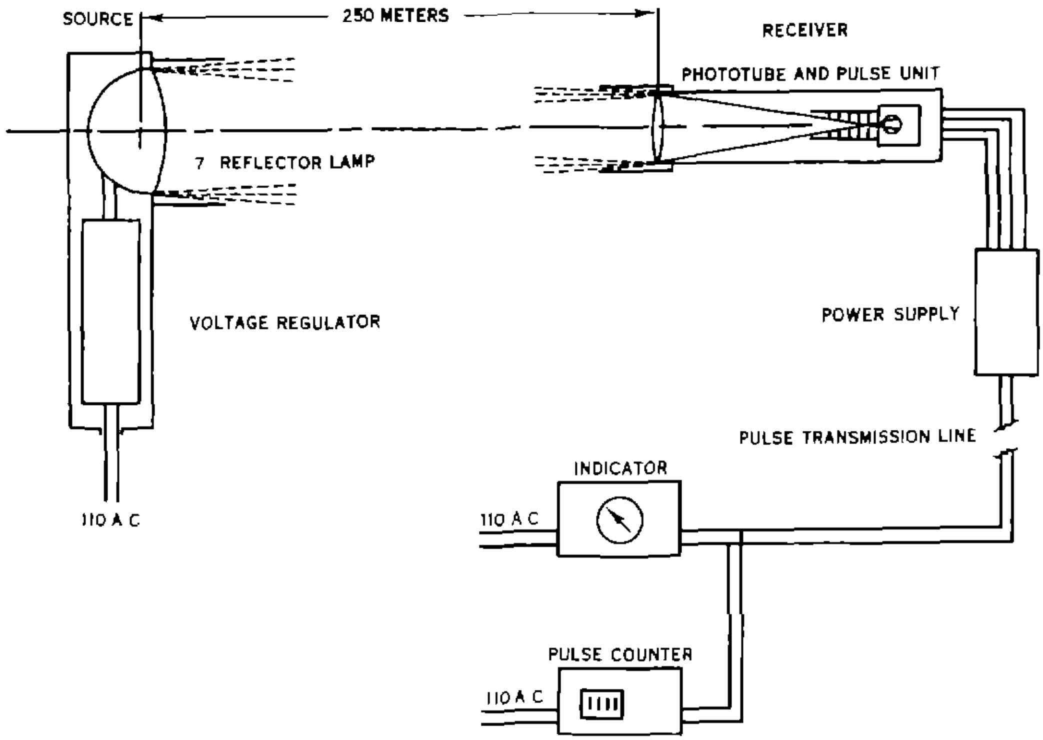

Figure 1 Schematic Diagram of Transmissometer

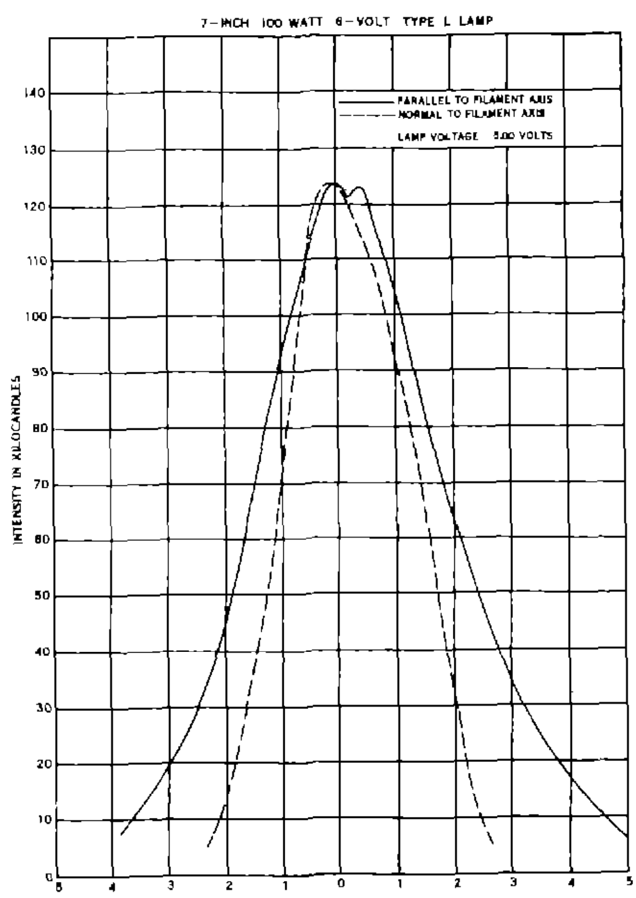

Figure 2 Candlepower Distribution

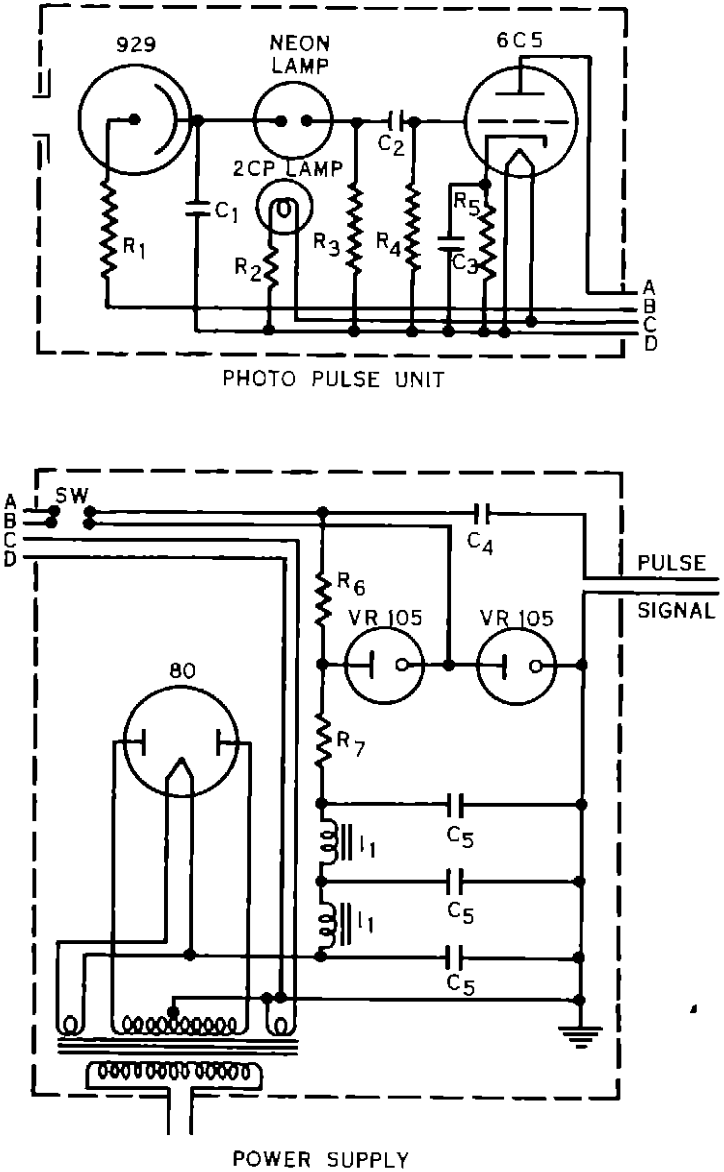

Figure 3 Receiver Circuits

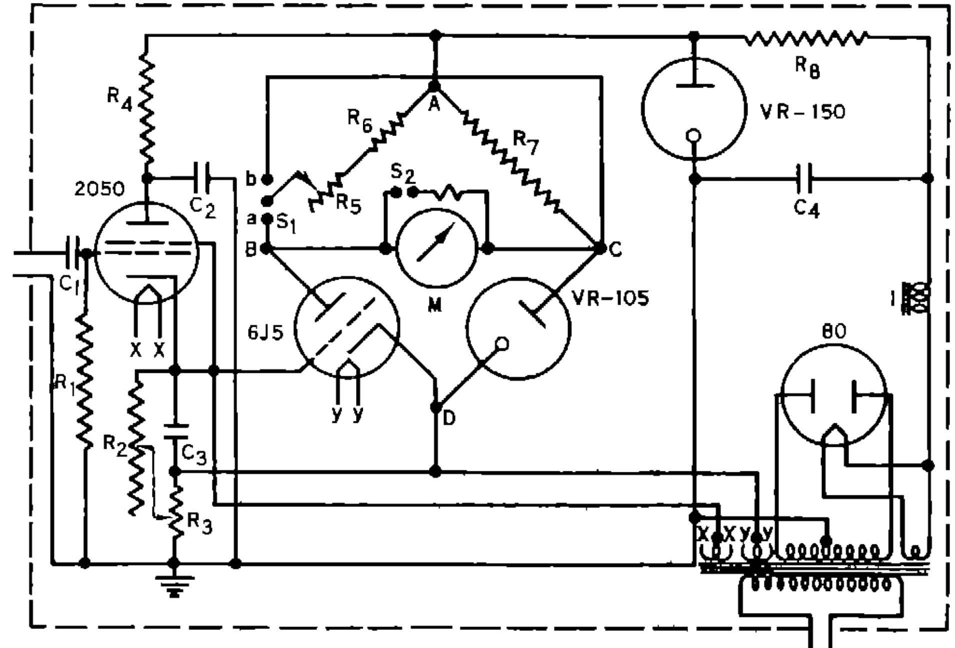

Figure 4 Indicator Circuit

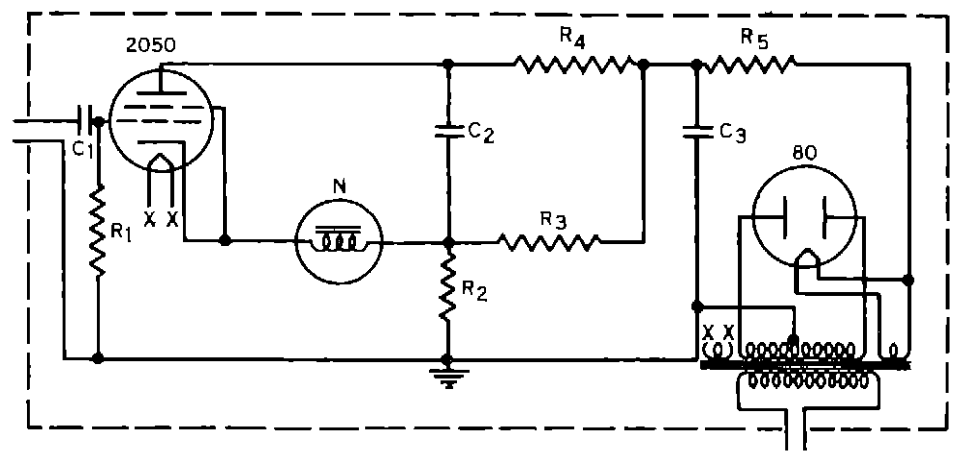

Figure 5 Counter Circuit

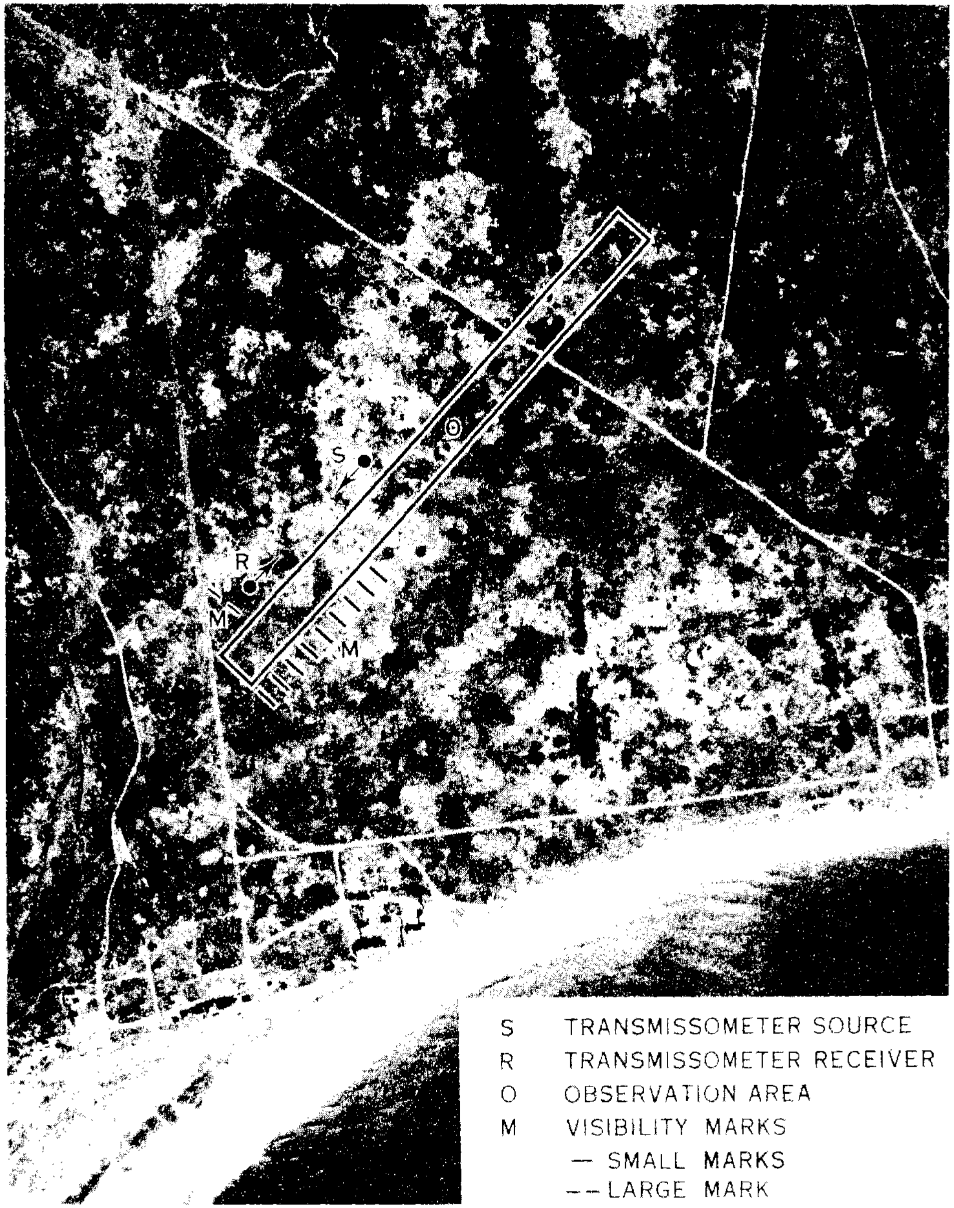

Figure 6. Location of Calibration Range.

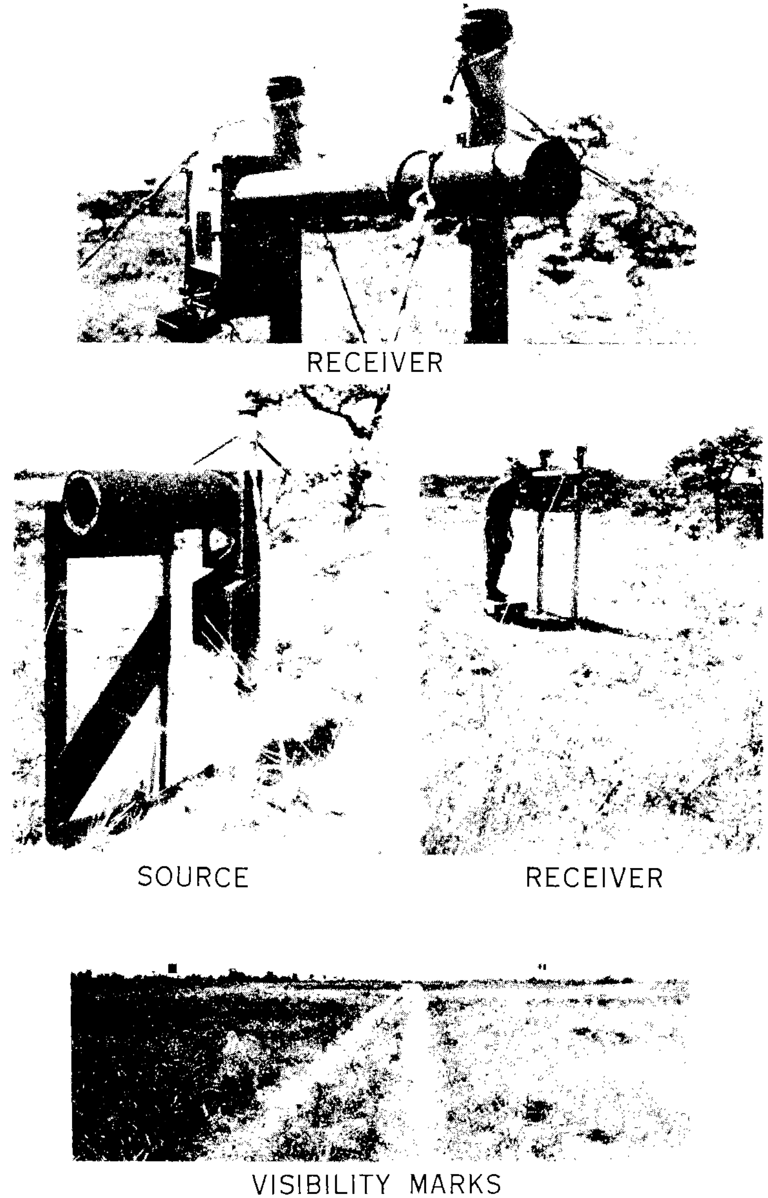

Figure 7. Field Installation.

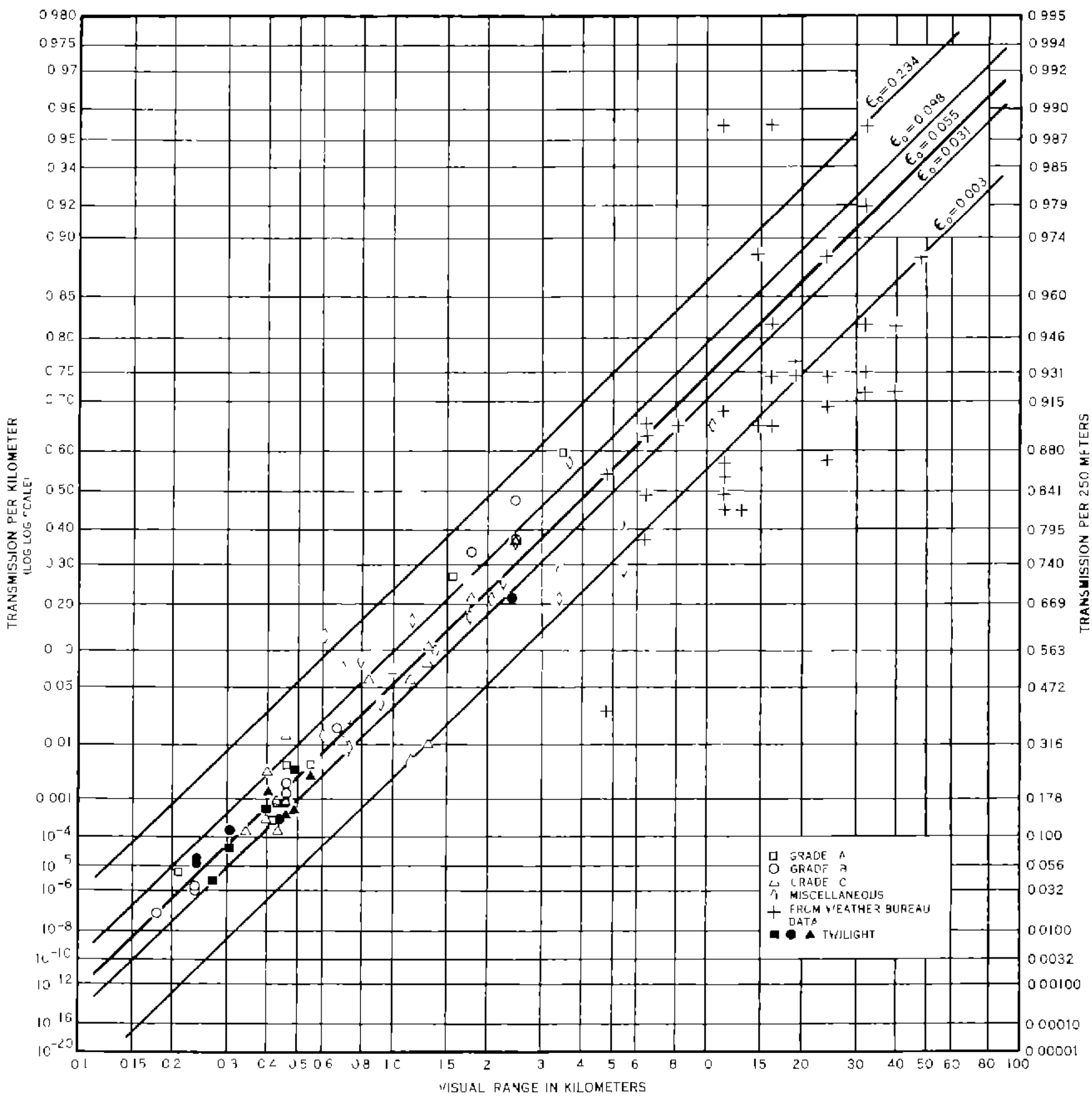

Figure 8 Daytime Transmissometer Calibration

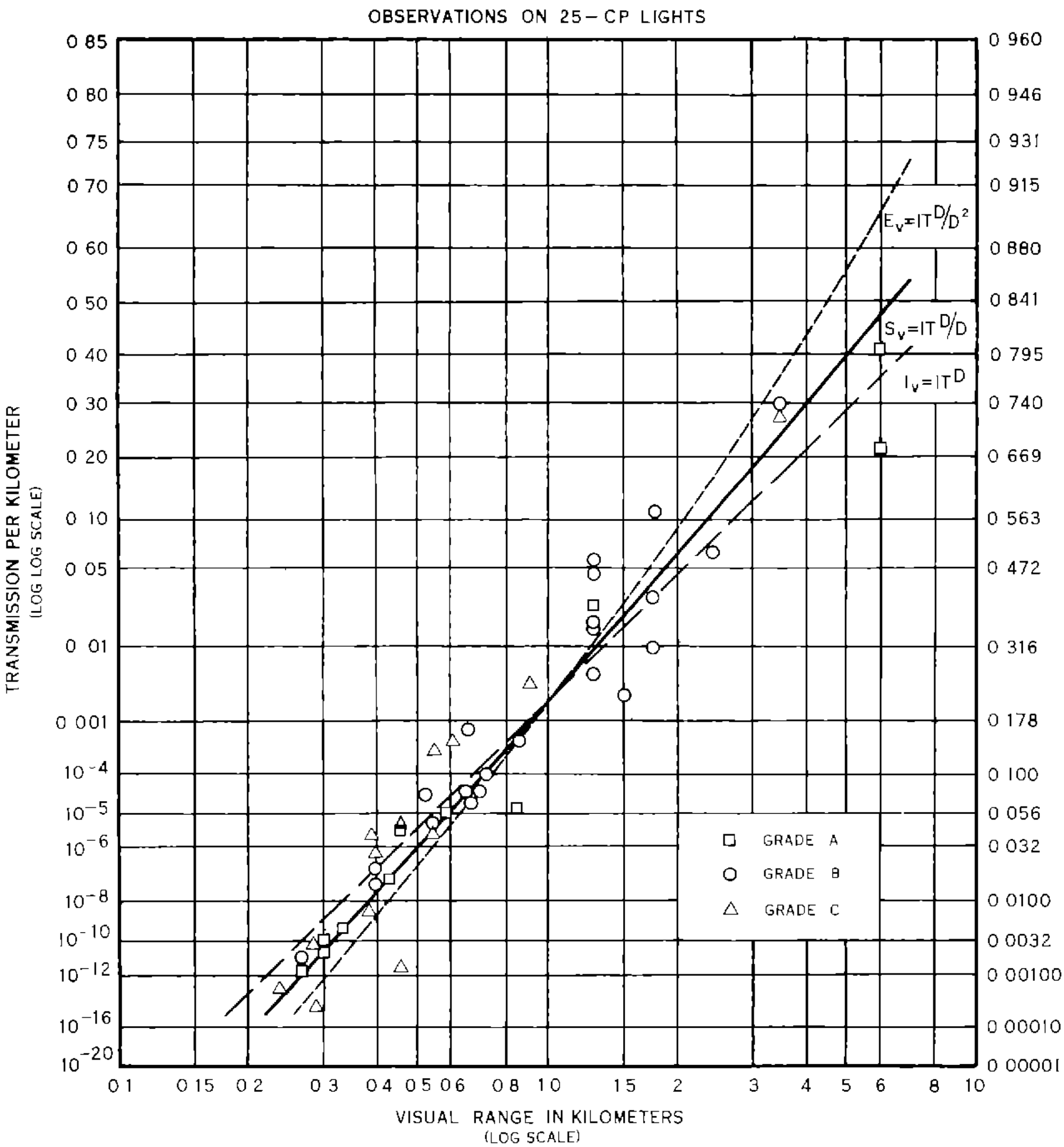

Figure 9 Nighttime Transmissometer Calibration

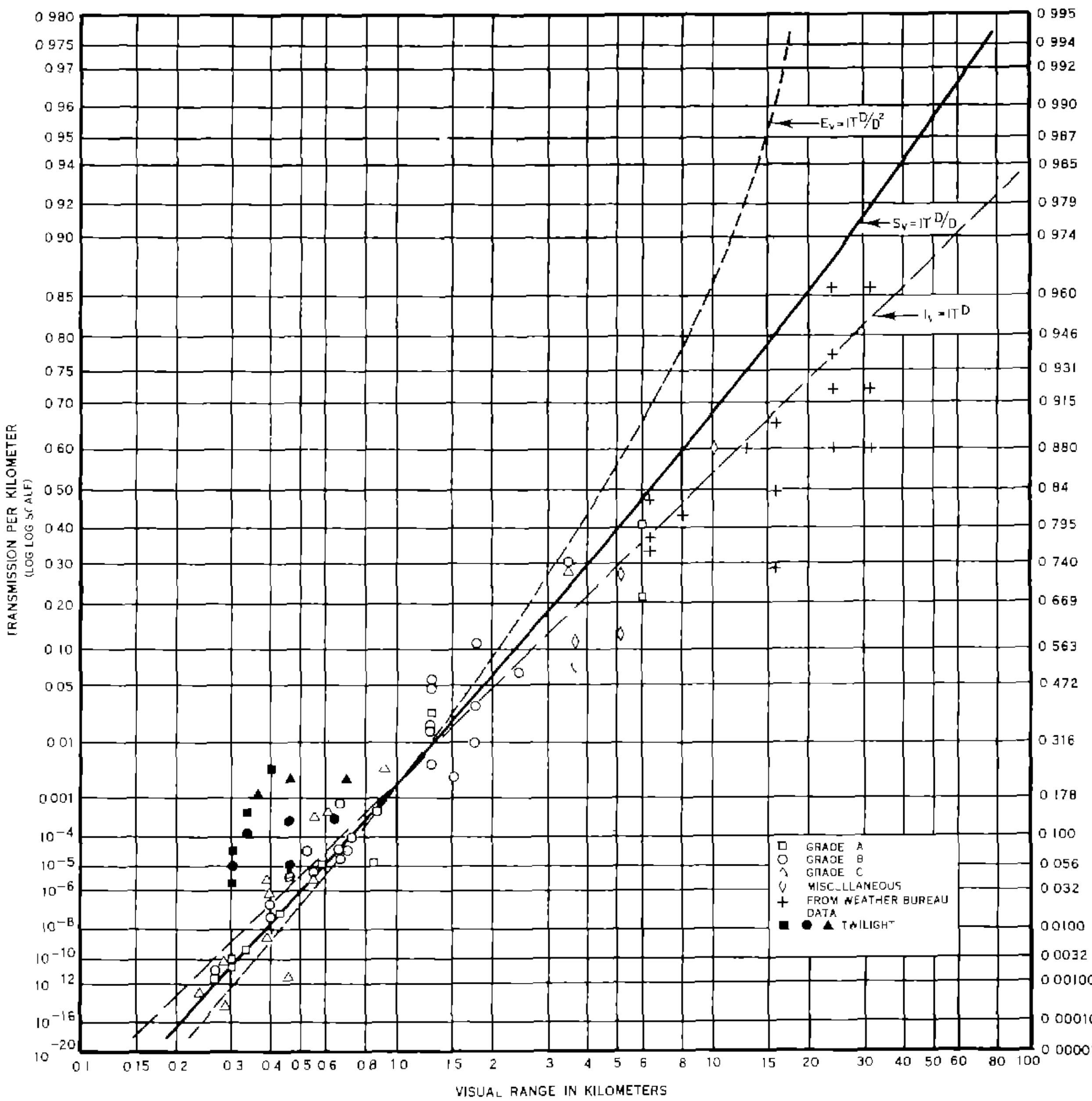

Figure 10 Nighttime Transmissometer Calibration