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Technical Memoranda

EXPERIMENTS TO DETERMINE

THE LUMINANCE CONTRAST THRESHOLD

A REVIEW

By

BRIAN E. SHEPPARD

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EXPERIMENTS TO DETERMINE THE LUMINANCE CONTRAST THRESHOLD - A REVIEW

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ABSTRACT

The World Meteorological Organization has recently proposed the adoption of meteorological optical range (MOR) as the standard meteorological and aviation visibility parameter. In order to ensure good agreement between this parameter and previous human visibility observations, an appropriate value for the luminance contrast threshold (ϵ) must be used in the calculation of MOR. This literature review lists values of ϵ along with brief descriptions of the experimental procedures used for their derivation. Factors affecting ϵ are emphasized so that the reader can determine those most relevant to his application. From the experimental evidence to date, we are only able to conclude that the ϵ value for the WMO application falls somewhere within the range, 0.02 to 0.05.

EXPÉRIENCE VISANT A DÉTERMINER LE SEUIL DE CONTRASTE DE LA LUMINANCE - COMPTE RENDU DE PUBLICATIONS

par

Brian E. Sheppard

RÉSUMÉ

L'Organisation météorologique mondiale a récemment proposé l'adoption de la portée optique météorologique (POM) comme paramètre standard de la visibilité météorologique et aéronautique. Afin d'assurer la concordance entre ce paramètre et les observations antérieures de la visibilité effectuées par des observateurs, il faut trouver un seuil de contraste de la luminance (ϵ) approprie pour le calcul de la POM. Le présent compte rendu de publications comprend la liste des valeurs de ϵ, ainsi que de brèves descriptions des méthodes expérimentales employées pour leur obtention. On souligne les facteurs qui influencent ϵ afin que le lecteur puisse déterminer ceux qui toucheront le plus l'application qu'il compte en faire. D'après les conclusions des expériences jusqu'à maintenant, nous pouvons seulement conclure que la valeur de ϵ pour l'application de l'OMM est comprise entre 0.02 et 0.05.

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1.   Introduction

The Seventh Session of the Commission for Instruments and Methods of Observations (CIMO-VII) was held at Hamburg, Germany in July 1977. M. Etienne was appointed Rapporteur on Aerodrome Meteorological Observing Systems with a term of reference as follows:

> "To review the available literature and recommend the most suitable value of the contrast threshold ratio to be used in determining MOR[1] in order to ensure that the MOR is a good approximation of the daytime visibility as determined by human observers; and if it appears desirable, to encourage and report on further studies by Members".

Because the Canadian delegation was responsible for this term of reference, the Observational Systems Co-ordinating Committee of the Atmospheric Environment Service formed an ad hoc working group to:

(1) "examine the problems of implementation of the revised text of Chapter 10,[2] i.e. the use of MOR to determine "visibility" at manned and automatic stations.

(2) determine whether further tests should be carried out to decide on a suitable value for the luminance contrast threshold and if such tests are deemed necessary to recommend specific tests which will produce the desired information."

As a first step, this working group recommended that a literature search of field and laboratory experiments be compiled. This report is the result of that search.

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[1] MOR is an acronym for meteorological optical range.

[2] Chapter 10 of the WMO Guide to Meteorological Instrument and Observing Practices discusses the Measurement of Visibility.

2. Scope of this Survey

A brief description of the method and data analysis for each laboratory and field experiment is given in Section 4 where Table 1 summarizes the results. Comparisons of the wide range of ε values should keep in mind the variety of objectives, methodologies, and conditions affecting the results of each experiment.

For convenience these results are also compared on a logarithmic scale in Figure 1. Only experimental values considered applicable to meteorological requirements are included. For example, the results of Huculak und Blais (22) were excluded because the exposure time was 0.25 s and the background luminance corresponded to twilight.

In the laboratory experiments the parameters affecting ε were varied over wide ranges so that the values of ε varied significantly. Since it is difficult to tabulate the functional relationships involving these parameters, interested readers should consult graphs presented in the original studies referenced (see (26)). In general ε decreases as the area of the target, the background luminance, and the time of exposure increase.

For comparison we have selected, where available, values of these parameters most suitable for meteorological applications. Background luminances of 10^3 to 10^4 cd m^{-2}, target sizes greater than 0.5° in diameter, and exposure times of several seconds were considered to conform with normal daytime observing situations.

3. Luminance Contrast Threshold

3.1 Definition

The smallest absolute difference between two luminance stimuli which can cause a distinguishable brightness response of the human visual system is known as the "difference limen". This parameter is impractical because it is strongly dependent on the adaptation luminance of the eye. The ratio of the difference limen to the adaptation luminance is less dependent on the latter, particularly at the higher luminances corresponding to normal daytime levels. This ratio is called the luminance contrast threshold, ε , the parameter used to represent visual sensitivity to contrast in calculations of daytime visibility. In meteorological applications, the luminance of the background of the visibility target frequently determines the adaptation level. In such cases, ε is more specifically equal to the minimum ratio of the difference in luminance between a target and its background, to the background luminance, when the target is just discernible against its surroundings.

3.2 Methods of Determination

There are two approaches for measuring ε experimentally.

The first approach is direct and measures the contrast ratio of the target and its background, i.e., the ratio of the difference between their luminances to the background luminance. The observer's ε equals the contrast ratio when the target is just discernible against its background. The observer should adapt his eyes to the background luminance level prior to an experiment. Although this approach can be applied in the field using telephotometry, (cf. (13 and 27)) it is mainly used in the laboratory where experimental conditions can be controlled. Important factors are size and shape of target, level of background luminance, polarity of the contrast ratio, and exposure time for detection. In certain experiments several observers view targets simultaneously. The data may be analyzed statistically to remove the elements of chance and test their significance. In a few cases, values of ε are associated with specified probability levels of detection used in the experiments. Such statistical methods are beyond the scope of this summary and the reader is referred to (12) and (22).

The second technique is indirect, based on Koschmieder's law (1):

$$\varepsilon = t^{V/b}$$

where   t is the transmittance of the atmosphere,
         b is the baseline distance over which the transmittance is
              measured, and
         V is a visibility parameter.

This equation is based on a number of important assumptions including a "black" target and the absence of a source adding luminance to the background between the observer and the target. These assumptions are discussed in (24).

ε is then calculated from values of V and t obtained, respectively, from visual observation, and from either a transmissometer measurement or some other assessment (e.g., see (8) and (23)).

One of the pitfalls of this approach, as described by Middleton and Mungall (13), is the definition of V and how it is actually applied by the observer. The multitude of definitions is not reviewed here but the reader is referred to the excellent compendium in (25). The basic problem lies in the clarity with which the target can be seen. Gavrilov (16) defines three

(1) disappearance: the distance at which a target is at the point of complete assimilation with its background.

(2) detection: the distance at which the presence of a target can be detected.

(3) recognition: the distance at which a target can be recognized for what it is, e.g., a tree versus a tower, etc.

Other investigations, such as that of Douglas (9), used more quantitative systems to code clarity for calibrating the transmissometer. Middleton and Mungall concluded that the large range in ε values for various meteorological observers is due to this lack of a precise definition for human visibility observations.

4. Descriptions of Experiments

1. Koschmieder, 1924.

In 1924 when Koschmieder developed his visual range equation, he assumed ε to be equal to 0.02 for objects of a reasonable size, viewed in daylight. Although this was not derived experimentally it is quoted here because of the fundamental importance of his work.

2. Runge, 1929.

Laboratory measurements for different target sizes and adaptation luminances gave ε values between 0.05 and 0.055 for three undefined luminances and a target diameter of 0.5°.

3. Houghton, 1939.

A two-part experiment yielded ε values of 0.65 in clouds and 0.03 in fog from simultaneous visual range observations and transmittance measurements.

4. Shallenberger and Little, 1940.

This study derived an expression for the visual range of smoke columns from forest fires as viewed from a lookout tower. Visibility was assessed by an observer using an optical attachment to a binocular lens which was designed to reduce the contrast ratio by the introduction of a calibrated level of sky luminance into the optical path. Details of the determination of the value of 0.032 for ε were not given.

5. Hulburt, 1941.

Telephotometric measurements of the luminance of a "black" target (an opening in the end wall of an aircraft hanger) at a distance of 3.2 km were used to calculate the atmospheric transmittance. The distances at

which a natural target had just disappeared in the range 3.2 to 15 km were determined by an observer in clear air, haze, fog, drizzle, rain and snow. From a graphical comparison of his observed data with Koschmieder's theoretical relationship, Hulburt concluded that his data were in accordance with an ε value of 0.02. Douglas and Booker (25) later calculated an ε value of 0.027 from these data.

6. Möller, 1943.

In a laboratory experiment ε was measured for different target sizes and adaptation luminances: ε was 0.006 for a 0.5° diameter target and 10^3 cd m^{-2} luminance.

7. Kuhl, 1943.

Laboratory measurements of the difference limen were made at low adaptation luminances (less than 1 cd m^{-2}) for different target sizes having both positive and negative contrasts. For comparison Kuhl provided graphs of the earlier observations of Hoppe and Siedentopf (1937) and Siedentopf (1941). From these an ε value of 0.01 can be derived for a 0.5° diameter target at 10^3 cd m^{-2} luminance.

8. Bricard, 1944.

Bricard modified Koschmieder's law by replacing the atmospheric transmittance with parameters describing the physical characteristics of fog. From simultaneous measurements of the visual range of a dark target against the horizon sky, the fog droplet radius, and droplet number density, he calculated values of ε ranging from 0.0077 to 0.025 for six occasions when the visibility was less than 100 m. A best fit to the data gives an average value for ε between 0.01 and 0.02.

9. Douglas and Young, 1945.

Douglas and Young calibrated their transmissometer for the runway visual range application by plotting visual range observations of 4-ft square black visibility markers against 4-min average transmittance measurements on scales chosen to give a linear relationship based on Koschmieder's theory. Observers were given one minute to detect the targets and grade their clarity. Between 1300 to 2000 observations were selected according to atmospheric stability. A least squares fit to the data yielded the ε value of 0.055, used as a standard in North American RVR calculations since 1945.

10. Van Lear, 1945.

A research experiment used simultaneous transmittance measurements and visibility observations in clouds to calculate $\varepsilon = 0.024$ from Koschmieder's equation.

11. Blackwell, 1946.

In the most extensive experiment to date, involving over 100,000 observations, several observers searched for circular targets projected on a screen under controlled laboratory conditions.

For a 50% probability of detection ε ranged from 0.0025 to 1000 depending on target size, polarity of the contrast ratio, adaptation luminance, and target exposure time. $\varepsilon = 0.003$ is selected from the results as being the most suitable value for meteorological applications.

12. Lamar et al., 1947.

In a laboratory experiment, observers attempted to identify the location of a rectangular target, brighter than its background, using monocular vision and an artificial pupil. ε values for 62.5% probability of detection and a 3-s exposure time, were averaged for five observers at two background luminance levels corresponding to sunlit snow and twilight. The objective of this experiment was to determine ε as a function of target area, and the ratio of length to width for foveal, parafoveal and peripheral vision. For high background luminance, and target areas greater than 100 square minutes, meteorologically appropriate values of ε range between 0.01 to 0.02 for target length-width ratios between 2 and 20.

13. Middleton and Mungall, 1952.

Differences between laboratory and field values of ε were investigated by taking direct telephometric luminance measurements of a natural target, specified by a meteorological observer to be at his visual range, and its immediate background. From these, ε may be calculated directly. It was concluded that a spread of a factor of two results from the different ways in which the definition of visual range was applied by the observers, i.e., recognition of the target versus detection.

14. Sperry Gyroscope Co., 1954.

Sperry Gyroscope Company was contracted by the U.S. Air Navigation Development Board to evaluate the operational performance of meteorological equipment under low ceiling/visibility landing conditions as observed by pilots. ε was calculated from simultaneous measurements of transmittance and observations of visual range on standardized targets by meteorological observers.

15. United States Weather Bureau/Air Navigation Board, 1955.

When the atmosphere was stable and the visibility was less than three miles, visual range observations by a single observer and corresponding 4-min average transmittance measurements were substituted in Koschmieder's equation to obtain an ε value of 0.05.

16. Gavrilov, 1958.

This report summarizes previous Russian research and gives data for experiments but no details or bibliography. Gavrilov distinguishes three visibility criteria, defined in Section 3.2 above.

17. Gavrilov, 1962.

A field experiment calculated ε to be 0.03 using transmittance measurements and the distances at which natural and man-made targets could be detected.

18. Lefkowitz and Schlatter, 1966.

The objective of this field experiment was to validate the Runway Visual Range system. Visual range observations of black 3 x 5 ft targets located beside the runway at 1000-ft. intervals less than one mile distant, and corresponding transmittance measurements were used to calculate an ε value of 0.2. The authors suggest that this unusually high value was caused, in part, by the relatively small target sizes.

19. Konovalov, 1968.

By mathematically analysing the experimental data, Konovalov derived empirical relationships relating ε and the background luminance for a range of target dimensions. The resulting curves are in good agreement with Blackwell's results (11), with the exception that the discontinuity at the parafoveal-foveal transition is missing. The most suitable value of ε for meteorological applications was selected as 0.01.

20. Hering et al., 1971.

A field experiment was designed to calibrate a forward scatter visibility meter. When visual range observations of black, $\frac{1}{2}°$ targets at 1/16-mile intervals up to 1/2 mile, and radio antennae from 1/2 to 1 3/4 miles, were compared to visual range values calculated from transmissometer measurements using an ε value of 0.02, a standard error of estimate of $\pm$ 20% is obtained.

21. Blackwell, 1971.

The results obtained were a by-product of research into illumination variables affecting roadway visibility in fog, using model-scale simulation and man-made water-droplet fog. An observer determined the distances at which a model automobile disappeared in fogs of different transmittances as measured by transmissometer under various intensities of illumination. The conditions best simulating meteorological applications were chosen to calculate ε equal to 0.037.

22. Huculak and Blais, 1973.

This laboratory experiment measured the values of ε for automobile drivers at luminance levels equivalent to night-time driving conditions. Square targets, rear projected on a translucent screen, were viewed for 0.25 s. The screen luminance and target sizes were controlled. By statistically analysing several hundred observations, ε for a 50% probability of detection was determined to be 0.019.

23. Muench and Brown, 1977.

A field experiment was set up to evaluate the operation of the forward scatter visibility meter in snow conditions. The visual ranges of 20 targets between 150 to 2500 m distant and 15-min means of the extinction coefficient measured by the forward scatter meter were used to calculate an ε value of 0.031.

There is a standard error of estimate of $\pm$ 15% when visibilities calculated from the measured extinction coefficients using $\varepsilon = 0.031$ are compared to visual range observations.

5. Conclusions

The results presented in Figure 1 should be interpreted with caution to ensure that the experimental conditions and analysis procedures agree with those of the user's application.

For example, several factors result in higher values of ε in most aviation applications than are achieved under laboratory conditions (cf. (26)). Laboratory experiments use probability levels for detection which are much lower than those which would be acceptable to the aviation industry. Also the exposure time in these experiments may exceed a pilot's search time to detect a target. In general, laboratory tests deal with stationary targets; whereas pilots are concerned with moving ones.

The meteorological need is to select ε so that MOR and daytime visual range are equivalent; therefore, the recognition versus detection criteria discussed in Section 3 must be considered.

The value of 0.05 proposed at CIMO-VII in Hamburg, Germany, (see Figure 1) is greater than the majority of values derived from field experiments. Koschmieder's assumed constant of 0.02 is near the lower limit value of the field experiments involving recognition of targets. This is confirmed by Hoffman's data analysis (27).

Therefore for meteorological applications involving the recognition of visibility targets ε has not been defined more accurately than the range 0.02 to 0.05.

6.   Acknowledgements

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TABLE 1

Summary of Experiments to Determine The Luminance Contrast Threshold ε

REF NO.	EXPERIMENTER	DATE	LOCATION	VALUE OF ε	NUMBER OF OBSERVATIONS	EXPERIMENTAL CONDITIONS
1.	KOSCHMIEDER, H.	1924		0.02		DEFINED CONSTANT
2.	RUNGE, I.	1929	BERLIN, GERMANY	0.05-0.055		LABORATORY, TARGET DIAMETER 0.5°
3.	HOUGHTON, H.G.	1939	MT. WASHINGTON, N.H.	0.06	30	CLOUDS
			ROUND HILL, MASS.	0.03 (0.016 to 0.06)		FOG
4.	SHALLENBERGER, G.D. LITTLE, E.M.	1940	MISSOULA, MONT.	0.032		HAZE AND SMOKE
5.	HULBURT, E.O.	1941	WASHINGTON, D.C.	0.027		ALL WEATHER CONDITIONS
6.	MÖLLER, F.	1943	GERMANY	0.006		LABORATORY
7.	KÜHL, A. HOPPE and SIEDENTOPF SIEDENTOPF	1943 1937 1941	JENA, GERMANY	0.01		SUMMARY OF RESULTS LABORATORY, TARGET DIAMETER 0.5°, BACK-GROUND LUMINANCE = 10^3 cd/m^2
8.	BRICARD, J.	1944	PARIS, FRANCE	0.0077 to 0.025		FOG
9.	DOUGLAS, C.A. YOUNG, L.L.	1945	NANTUCKET ISLAND, MASS.	0.055 (0.031 to 0.098)	1300 to 2000	MOSTLY FOG

TABLE 1

Summary of Experiments to Determine The Luminance Contrast Threshold ε (Cont'd)

REF NO.	EXPERIMENTER	DATE	LOCATION	VALUE OF ε	NUMBER OF OBSERVATIONS	EXPERIMENTAL CONDITIONS
10.	VAN LEAR, G.A., JR.	1945	MT. WASHINGTON, N.H.	0.024	285	CLOUD
11.	BLACKWELL, H.R.	1946	OYSTER BAY, N.Y.	0.003	10^5	LABORATORY, TARGET 0.5°, BACKGROUND LUMINANCE = 10^3 cd/m^2, UNLIMITED EXPOSURE TIME, 50% PROBABILITY OF DETECTION
12.	LAMAR, E.S. HECHT, S. SCHLAER, S. HENDLEY, C.D.	1947	COLUMBIA UNIVERSITY NEW YORK	0.01 to 0.02	100	LABORATORY TARGET AREA 100 SQ. MIN., HIGH BACKGROUND LUMINANCE, 3-S EXPOSURE TIME, 62.5% PROBABILITY OF DETECTION
13.	MIDDLETON, W.E.K. MUNGALL, A.G.	1952	ROCKCLIFFE, ONT.	0.030 (0.015 to 0.06)	1000	ALL WEATHER CONDITIONS
14.	SPERRY GYROSCOPE CO.	1954	MACARTHUR FIELD, LONG ISLAND, N.Y.	0.065	72	RADIATION FOG
				0.030	6	SNOW
				0.042	58	LOW CLOUDS OR FOG
15.	U.S. WEATHER BUREAU AIR NAVIGATION BOARD	1955	WASHINGTON NATIONAL AIRPORT	0.05	112	FOG AND SMOKE

TABLE 1

Summary of Experiments to Determine The Luminance Contrast Threshold ϵ (Cont'd)

REF NO.	EXPERIMENTER	DATE	LOCATION	VALUE OF ϵ	NUMBER OF OBSERVATIONS	EXPERIMENTAL CONDITIONS
16.	GAVRILOV, V.A.	1958	RUSSIA			SUMMARY OF PREVIOUS STUDIES BY RESEARCHERS LISTED BELOW ACCORDING TO THREE VISIBILITY CRITERIA
	SHARONOV, U.V.		RUSSIA	0.015		LABORATORY AND FIELD, DISAPPEARANCE
	SYTINSKAYA, N.N.		RUSSIA	0.015		LABORATORY AND FIELD, DISAPPEARANCE
	DASHKEVICH, L.L.		RUSSIA	0.018		LABORATORY AND FIELD, DISAPPEARANCE
	BARTENEVA, O.D.		RUSSIA	0.05		FIELD, DETECTION
	KONIG, A.E. BRODHUN, E.	1888	GERMANY	0.02		LABORATORY, DETECTION
	GAVRILOV, V.A.		RUSSIA	0.019 0.025 0.035		FIELD, DISAPPEARANCE DETECTION RECOGNITION
	FOITZIK, L.		GERMANY	0.018 0.04		LABORATORY AND FIELD, DISAPPEARANCE DETECTION

TABLE 1

Summary of Experiments to Determine The Luminance Contrast Threshold ε   (Cont'd)

REF NO.	EXPERIMENTER	DATE	LOCATION	VALUE OF ε	NUMBER OF OBSERVATIONS	EXPERIMENTAL CONDITIONS
	SCHÖNWALD, B.		GERMANY	0.014		LABORATORY,DISAPPEARANCE
	TASSEL AND OLIVER		?	0.08		FIELD, 15-S EXPOSURE TIME FOR RECOGNITION
	GAVRILOV, V.A.		RUSSIA	0.07 ± 0.02		FIELD, 15-S EXPOSURE TIME FOR RECOGNITION
17.	GAVRILOV, V.A.	1962	RUSSIA	0.03		FIELD
18.	LEFKOWITZ, M. SCHLATTER, E.E.	1966	NAFEC, ATLANTIC CITY, N.J.	0.2	46	ALL WEATHER CONDITIONS
19.	KONOVALOV, Iu..G.	1968	RUSSIA	0.01		LABORATORY, TARGET DIAMETER 0.5°, AVERAGE DAYLIGHT BACKGROUND LUMINANCE
20.	HERING, W.S. MUENCH, H.S. BROWN, H.A.	1971	CUTLER, ME.	0.02	200	FOG
21.	BLACKWELL, H.R.	1971	OHIO STATE UNIVERSITY	0.037		LABORATORY, IN SIMULATED FOG, DISAPPEARANCE
22.	HUCULAK, P. BLAIS, R.	1973	NATIONAL AERONAUTICAL ESTABLISHMENT, OTTAWA	0.019	1000	LABORATORY, 15' TARGET DIAMETER, 0.25-S EXPOSURE TIME
23.	MUENCH, H.S. BROWN, H.A.	1977	HASCOM AFB, MASS.	0.031	84	SNOW

FIGURE 1
COMPARISON OF SELECTED
VALUES OF ϵ FROM TABLE 1
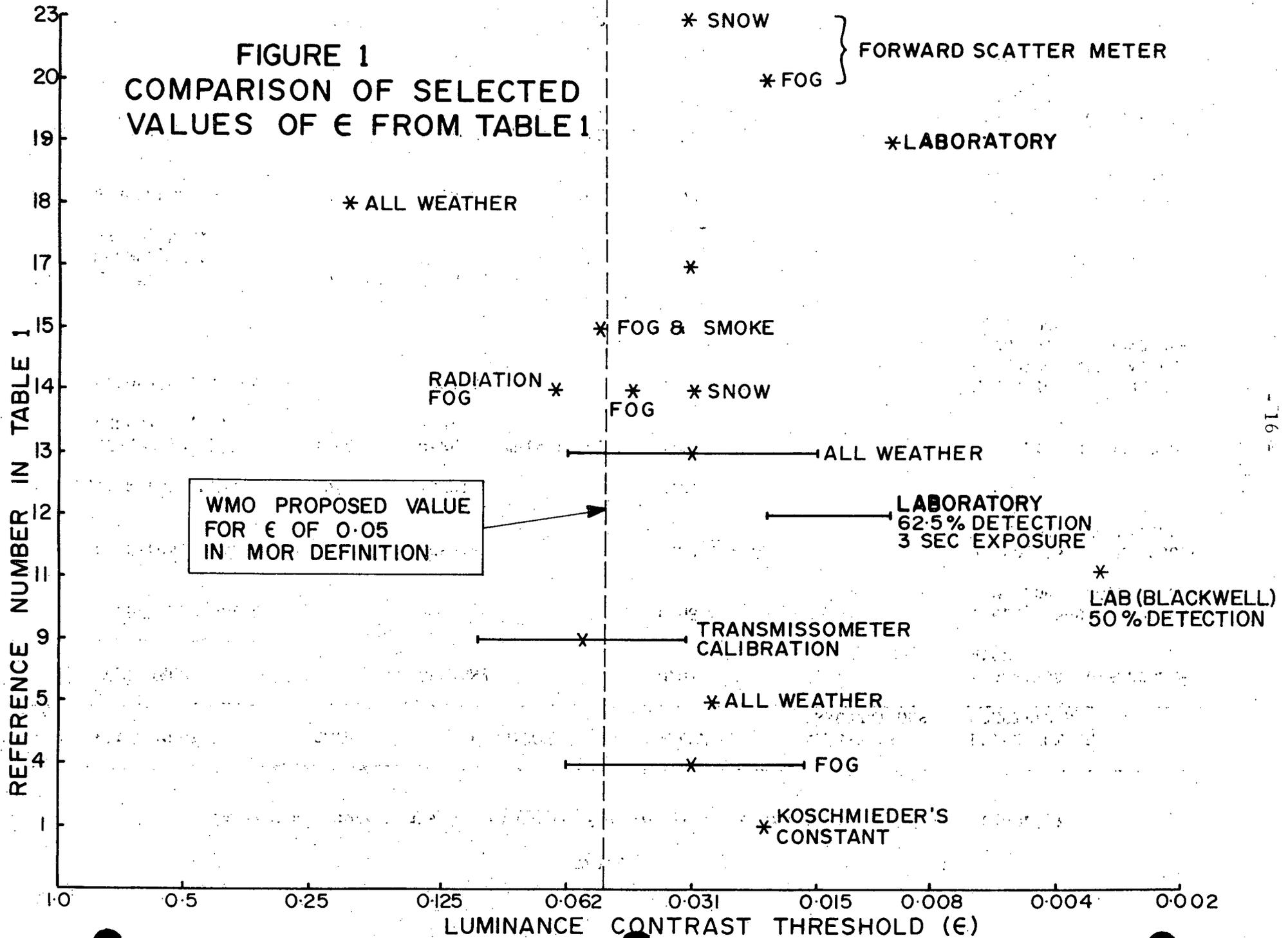
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9 pp. 27 Refs. 1 Figure 1 Table

Subject Reference: 1. luminance contrast threshold
2. met. optical range

ABSTRACT: The World Meteorological Organization has recently proposed the adoption of meteorological optical range (MOR) as the standard meteorological and aviation visibility parameter. In order to ensure good agreement between this parameter and previous human visibility observations, an appropriate value for the luminance contrast threshold (ϵ) must be used in the calculation of MOR. This literature review lists values of ϵ along with brief descriptions of the experimental procedures used for their derivation. Factors affecting ϵ are emphasized so that the reader can determine those most relevant to his application. From the experimental evidence to date, we are only able to conclude that the ϵ value for the WMO application falls somewhere within the range, 0.02 to 0.05.