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NIGHTTIME VISIBILITY

By

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TABLE OF CONTENTS

Introduction Nighttime Visibility 1

Meteorological Visibility 1

Daytime Visibility 1
Nighttime Visiblity 2
Runway Visual Range 4

Method of Measuring Attenuation 4

Illuminance Difference 4
Luminance Difference 5
Error Analysis 6

Summary 7

Table 1 Twice liminal illuminance differences for confident sightings 9

Figure 1 Visibility or visual range as a function of attenuation coefficient 10

Figure 2 Luminance error factors 11

References 12

Appendix Table A1 Visibiity and runway visual range for Figure 1. 13

Appendix Table A2 Luminance error factors for Fig. 2 14

NIGHTTIME VISIBILITY

Visibility is essentially a function of the average attenuation coefficient. This relationship is discussed for daytime, twilight and nighttime. A method using horizon scanning imager measurements of the apparent luminance of lights of opportunity to obtain the average attenuation coefficient is described. An error analysis follows of the defining equation.

METEOROLOGICAL VISIBILITY

The following description of visibility is primarily based on the Bureau of Standards review of visibility principles, procedures and equipments by Douglas and Booker (1977).

Visibility, or meteorological visibility, is a term used to describe the clarity of the atmosphere in units of distance. The federal and world meteorological handbooks define daytime visibility separately from nighttime visibility. Daytime (and twilight) visibility is the greatest distance at which dark objects can be seen and identified against the horizon sky. Nighttime visibility is the greatest distance at which lights of moderate intensity (25 candles) can be seen and identified.

Most countries use the daytime definition for both daytime and nighttime visibility. This allows a one-to-one correlation with atmospheric transmittance which does not change between day and night.

In North America and specifically in the United States, the two separate daytime and nighttime definitions are used. Thus in the United States there is a different relationship between the attenuation coefficient and the visibility for daytime and nighttime.

The relationships of the attenuation coefficient α or beam transmittance T_r to the daytime, twilight and nighttime visibility V are based primarily on experiments made during field trials of the Douglas transmissometer during the 1940s in Nantucket.

DAYTIME VISIBILITY

The daytime visibility is based on the Koshmeider equation for the contrast transmittance of a black object against the horizon sky (Eq. 2.16, Douglas and Booker, 1977)

$$C_r = T_r = \exp(-\alpha\, r) \qquad (1)$$

Based on a contrast threshold C_r of 0.055 from the Nantucket experiment, the transmittance from a transmissometer of length r is converted to the visibility V by

$$V = r \ln 0.055 / (-\ln T_r) \qquad (2)$$

Similarly, the daytime visibility can be obtained from the attenuation coefficient by

$$V = -\ln 0.055 / \alpha = 2.9/ \alpha \ . \qquad (3)$$

The daytime visibility is graphed as a function of attenuation length which is the reciprocal of the attenuation coefficient in Fig. 1. The abscissa is marked in attenuation coefficient and transmittance per kilometer as well as attenuation length.

The contrast threshold is sometimes rounded to 0.05 ($\ln 0.05 = 3$) making the daytime visibility comparable to the Meteorological Optical Range which is defined by a transmittance of 0.05.

The Nantucket experiments tested the visibility of black targets seen against the horizon sky during twilight, as well as during daylight. Although the average contrast threshold for these data was slightly lower than for the daytime, the difference was not large. It is thus quite reasonable to include twilight in the daytime definition.

NIGHTTIME VISIBILITY

Nighttime visibility is defined in terms of the distance 25-candle-lights can be seen and identified. This makes the visibility dependent not only on the threshold illuminance difference assumed for the observer, but also on the intensity of the lights. The threshold illuminance difference for determining nighttime visibility would be expected to be based on Allard's law for illuminance, modified to obtain the illuminance difference (as is needed for visual thresholds at other than zero background luminance. The illuminance difference can be devined as (Eq. 1 in Gordon, et al. , 1975)

$$\Delta E = ({}_tL_r - {}_bL_r)\Omega = \Delta L_r \Omega \ . \qquad (4)$$

Allard's law expressed in terms of illuminance difference is

$$\Delta E = (I - {}_bL_o A)\, T_r / r^2 \ . \qquad (5)$$

This equation cannot be solved algebraically, but is relatively easy to solve by iterative or nomographic means. The signal light nomogram (Gordon, et al. , 1975) is a nomographic solution for Eq. 5 using the twice liminal Tiffany data for the threshold illuminance difference.

The effective luminance of a 25 candle light (assuming a 2 inch diameter light) is equal to 12,300 lumens/steradian square meter (3,600 foot lamberts). Thus, within a precision of 2 percent or better, for all twilight and nighttime horizon luminances, Eq. 5 becomes

$$\Delta E = I\, T_r / r^2 \ . \qquad (6)$$

At this point, it is appropriate to note that although Eq. 6 cannot be solved directly, the upper limiting range can be solved directly by assuming the transmittance to be one. The upper limit on range for any given illuminance threshold and light intensity is

$$\text{limiting } r = (I/\Delta E)^{1/2} \ . \qquad (7)$$

Measurements of the horizon luminance near runways during nighttime (Douglas and Booker, 1977, p. 7-24) indicated luminances near 0.01 millilamberts (0.00929 footlamberts). This is roughly equivalent to the horizon luminance for the sun at a 10° depression angle with no moon or with a full moon

regardless of solar depression angle. For a 45° latitude, it only takes one hour from sunset for the sun to be at -10° throughout the year (Brown, 1952).

Further decreases in the horizon luminance do not appreciably change the threshold since it has nearly reached an asymptote for the fovea. The foveal twice liminal illuminance differences for background luminances 340 through 0.000034 lumens/steradian square meter (100 through 0.00001 footlamberts) sunset through overcast starlight are given in Table 1. The threshold illuminances are for twice liminal Tiffany and 1/3 second fixation times. For the 1/3 second values the Blondel Rey equation is used,

$$\Delta E_t = \Delta E_\infty \, (\Delta t' + \Delta t)/\Delta t \ . \qquad (8)$$

The $\Delta t'$ values are from Table I and the ΔE_∞ are the twice liminal Tiffany values from Table IV in Gordon (1971).

The experimental observations at Nantucket for nighttime were fitted to Eq. 6 assuming a threshold illuminance of 0.052 lumens/square kilometer (which is roughly midway between the illuminance difference for the Tiffany and the 1/3 second fixations in Table 1 for 0.01 foot-lamberts). This curve did not fit the data as closely as did an empirical curve based on the equation

Fig 7.5 in Duntley & Boileau

$$S = I \, T_r / \, r \ . \qquad (9)$$

Equation 9 is considered the defining equation for nighttime visibility with S = 0.052 lumens/kilometer and I = 25 candles. This can be rewritten as

$$0.00208 \text{ km} = T_r/r \ . \qquad (10)$$

Again, it can be solved iteratively but not directly. Equation 9 was explained as indicating that at night the observer's illuminance threshold increases due to glow from the source being observed at the closer ranges (the threshold increases as the visual range decreases). In addition, however, Eq. 10 changes the definition of the upper limiting range, which becomes

$$\text{limiting } r = I/\Delta E \ . \qquad (11)$$

Thus the limiting range has been increased from the square root of the intensity to illuminance ratio to the ratio (from 219 to 481 kilometers for a threshold of 0.052 lu/km and a 25 candle light).

The visibility based on Eq. 6 for the twice liminal Tiffany, 0.052 lumens/square kilometer, and 1/3 second fixation thresholds are also graphed in Fig. 1, as is Eq. 10. The differences at the shorter ranges are relatively small but at the higher air clarities closer to the Rayleigh limit, the differences are very large since the limiting range has been increased. The effect of using Eq. 10 at the higher air clarities is to assume the visibility to be enhanced at the longer ranges but no physical mechanism can explain this increase in the limiting range.

I believe this anomally occurred because the emphasis on the visibility measurements was for the shorter ranges. The closely controlled portions of the Nantucket experiment were for ranges 0.25 to 3.5 kilometers. The data for the longer ranges were for miscellaneous targets.

RUNWAY VISUAL RANGE

Runway Visual Range is distinct from the visibility. Runway Visual Range is defined as the maximum distance in the direction of take-off or landing at which the runway or 10,000 candle lights can be seen from a height of 5 m assuming an illuminance threshold of 1000 mile-candles (386 lu/km^2) for daytime and 2 mile-candles (0.772 lu/km^2) for nighttime. Equation 6 (Allard's Law) is assumed for the runway visual range. Values of runway visual range are also graphed in Fig. 1 for comparison.

Runway Visual Range has a slightly different definition in Europe. Different thresholds are used: 2600 mile-candles (1000 lu/km^2) bright daylight, 780 mile-candles (301 lu/km^2) overcast, and 2.6 mile-candles (1 lu/km^2) at night.

For a much fuller discussion of the history and background of both Visibility and Runway Visual Range, please refer to Douglas and Booker (1977). The curves in Figure 1 relate the attenuation coefficient to nighttime and daytime visibility, and Runway Visual Range as they are used in the United States.

METHOD OF MEASURING ATTENUATION

The following is a scheme for obtaining a nighttime average attenuation coefficient α using the horizon scanning imager on lights of opportunity. A series of similar lights, i.e., runway lights, or street lights which can be assumed equivalent (although of unknown intensity) is needed where the distance or range r to each light is known. The effect of small differences in intensity can be taken into account and nullified by measuring a number of lights and averaging the resultant attenuation coefficients. Making a number of measurements in different directions also allows the attenuation coefficient to be averaged. The prevailing visibility is the median visibility around the horizon circle.

I have derived this in two ways starting with the basic equations for 1) illuminance differences and 2) luminance differences and have obtained the same resultant equation.

ILLUMINANCE DIFFERENCE

The illuminance difference ΔE is the illuminance at the collector over and above the illuminance if the light were not present. The illuminance difference is equal to the apparent luminance of the light at the collector minus the luminance of its surrounding background, times the solid angle of the collector Ω (Eq. 1 of Gordon, et al.,1975) Eq. 4 repeated from above,

$$\Delta E = ({}_tL_r - {}_bL_r)\Omega = \Delta L_r \Omega \ . \qquad (4)$$

Also the illuminance difference is a function of the difference between the light intensity and the effective intensity of the background, times the beam transmittance divided by the square of the distance or range, Eq. 5 repeated from above,

$$\Delta E = (I - {}_bL_o\, A)\, T_r / r^2 \ . \qquad (5)$$

The effective intensity of the background is the luminance of the background times the projected area A of the light.

Now substituting Eq. 4 into Eq. 5 we get

$$\Delta L_r \, \Omega = (I - {}_bL_o \, A) \, T_r / r^2 \, . \qquad (12)$$

Rearranging slightly

$$r^2 \, \Delta L_r \, \Omega = (I - {}_bL_o \, A) \, T_r \, . \qquad (13)$$

Obtaining measures of apparent radiance difference at two different ranges r_1 and r_2, and ratioing their substitutions in Eq. 13 we obtain

$$r_1^2 \Delta L_{r1} \Omega / (r_2^2 \Delta L_{r2} \Omega) = (I - {}_bL_{o1} A) T_{r1} / [(I - {}_bL_{o2} A) T_{r2}] . \qquad (14)$$

Since the solid angle Ω of the collector is constant, this drops out. Then, if we can assume that either: a) the effective inherent background intensity (${}_bL_o \, A$) is essentially zero or negligible in comparison to the intensity of the lamp or b) the inherent background luminances ${}_bL_{o1}$ and ${}_bL_{o2}$ are sufficiently equivalent, Eq. 14 simplifies to

$$r_1^2 \, \Delta L_{r1} / (r_2^2 \, \Delta L_{r2}) = T_{r1} / T_{r2} = \exp[\alpha \, (r_2 - r_1)] \, . \qquad (15)$$

Taking the log of both sides we get an expression for attenuation coefficient α.

$$\alpha = \ln[r_1^2 \, \Delta L_{r1} / (r_2^2 \, \Delta L_{r2})] / (r_2 - r_1) \, . \qquad (16)$$

This is the equation for computing the attenuation coefficient based on the measurement of the apparent luminance of two similar lights at two distances. The apparent luminance difference is the apparent radiance of the light minus the apparent luminance of the background adjacent to the light.

LUMINANCE DIFFERENCE

The apparent luminance difference is a function of the inherent luminance difference times the beam transmittance (Eq. 5, Duntley, et al., 1957),

$$\Delta L_r = \Delta L_o \, T_r \, . \qquad (17)$$

The inherent luminance difference appropriate for this equation must take into consideration that the solid angle of the collector probably encompasses not only the light but some of the background as well. Thus the effective inherent luminance of the light is an average of the inherent luminance of the light (I/A), weighted by the area of the lamp A and the luminance of the surrounding background, weighted by the remaining area (A_c - A) in the field of view of the collector as follows:

$$\Delta L_o = [I \, A/A + {}_bL_o \, (A_c - A)] / A_c - {}_bL_o \, . \qquad (18)$$

This simplifies to

$$\Delta L_o = [I - {}_bL_o \, A] / A_c \, . \qquad (19)$$

Since the collector solid angle can be expressed as a function of the projected area in the field of view of the collector and the range ($\Omega = A_c/r^2$) we can now rewrite Eq. 17 as

$$\Delta L_r = [I - {}_bL_o\, A]\, T_r /(\Omega\, r^2) \,. \qquad (20)$$

Equation 20 is equivalent to Eq. 12 slightly rearranged.

ERROR ANALYSIS

Equation 16 is the defining equation for determining the attenuation coefficient using the horizon scanning imager on a series of similar lights such as runway lights, or street lights. However, for the error equation to be complete we will return to Eq. 14 in order to include in the evaluation the potential error in using similar but not exactly equivalent intensity lights. Let us slightly rewrite Eq. 14 as follows

$$\alpha = \ln[r_1^2\, \Delta L_{r1}\, \Delta I_2 /(r_2^2\, \Delta L_{r2}\, \Delta I_1)]/\, \Delta r \,, \qquad (21)$$

The incremental luminance is defined as the target or light luminance minus the background luminance

$$\Delta L_r = {}_tL_r - {}_bL_r \,. \qquad (22)$$

The effective incremental intensity is defined as

$$\Delta I = I - {}_bL_o\, A \qquad (23)$$

and the incremental range is defined as

$$\Delta r = r_2 - r_1 \,. \qquad (24)$$

The error equation for Eq. 21 is

$$\begin{aligned} d\alpha/\alpha = (\alpha\, \Delta r)^{-1} [&F(t,r_1)d_tL_{r1}/{}_tL_{r1} - F(b,r_1)d_bL_{r1}/{}_bL_{r1} \\ &- F(t,r_2)d_tL_{r2}/{}_tL_{r2} + F(b,r_2)d_bL_{r2}/{}_bL_{r2} \\ &- F(r_2)dr_2/r_2 + F(r_1)dr_1/r_1 \\ &+ F(I_2)dI_2/I_2 - F(bo_2)d_bL_{o2}/{}_bL_{o2} \\ &- F(I_1)dI_1/I_1 + F(bo_1)d_bL_{o1}/{}_bL_{o1}]. \end{aligned} \qquad (25)$$

The factors on the proportional luminance error dL/L are for the light or target

$$F(t,r) = {}_tL_r/\Delta L_r \qquad (26)$$

and for the background

$$F(b,r) = {}_bL_r/\Delta L_r \,. \qquad (27)$$

The luminance error factors are graphed in Fig. 2. The abscissa is marked in the ratio of the background luminance divided by the target luminance. If

the apparent background luminance is no greater than one half the apparent luminance of the light, the luminance error factors are not excessive. It is important to note that the absolute error in the luminance measurements (assuming the same absolute error for each luminance measurement) subtracts out and only the random precision errors apply. Thus, an averaging of the attenuation coefficients obtained from a number of measurements not only averages the attenuation coefficient, but also averages out the random luminance precision errors.

Note that there is a multiplyer before the braces which surround the algebraic sum of all the errors. If the incremental range is equal to or greater than the attenuation length (the reciprocal of the attenuation coefficient) this multiplyer is one or less than one.

The range error factors are

$$F(r) = 2 + \alpha r \ . \tag{28}$$

Since the range error factor is always large (two plus the distance to the light divided by the attenuation length), it is imperative that the distance to the lights be accurately known.

The intensity error factors are defined as

$$F(I) = I/\Delta I \tag{29}$$

and

$$F(bo) = {}_bL_oA/\Delta I \ . \tag{30}$$

If the effective inherent background intensity of the light ${}_bL_oA$ is very small relative to the light intensity, then F(bo) is essentially zero and F(I) is one. In this case the intensity error Error(I) can be expressed as

$$Error(I) = [dI_2/I_2 - dI_1/I_1]. \tag{31}$$

Since I_1 and I_2 are assumed to be equivalent, the intensity differential dI should be the difference between the light intensity and the standard intensity. If I_1 is assumed the standard intensity, the intensity error becomes

$$Error(I) = [(I_2-I_1)/I_2-(I_1-I_1)/I_1] = [(I_2-I_1)/I_2]. \tag{32}$$

This error should be random in sign. An averaging of a number of values of attenuation coefficient from a series of measurements will tend to average out the random error due to slight differences in intensity between the two lights I_1 and I_2.

SUMMARY

A method is suggested using horizon scanner imager measurements of similar lights such as runway or streetlights to obtain an average attenuation coefficient. The attenuation coefficient can be computed from the apparent luminance of two lights and the apparent luminance of their adjacent backgrounds

using Eq. 16. It is important that the distance between the two lights be equal to or greater than the attenuation length (reciprocal of the attenuation coefficient) and that the distance from the horizon scanner imager to each light be accurately known. As far as possible, a number of measurements should be made in a number of directions so that 1) the attenuation coefficient can represent the prevailing attenuation, 2) the random precision error in the luminance measurements of the lights can be averaged out, and 3) the random error due to using lights of similar but not exactly equivalent light intensity can be averaged out in so far as possible.

The daytime and twilight meteorological visibility values are obtained from Eq. 3. The nighttime visibility is obtained from Eq. 10. There are tables and graphs (see Fig. 4.7 Douglas and Booker, 1977) available to convert from daytime to nighttime visibility or a program can be written to do this directly.

Table 1 Twice liminal illuminance differences for confident sightings

Background luminance	Background luminance	Tiffany 2X limen foveal delta E	Ratio to Minimum value	Blondel Rey Critical Duration	1/3 sec 2X limen Delta E	Ratio to Minimum value	Brown illuminance E	Description
Ft-lamberts	lu/ster sq m	lu/sq km		sec	lu/sq km		lu/sq ft	
1000.00000	3400.00000	66.90000						full daylight
100.00000	340.00000	9.08000	370.61	.122	12.4033	163.47	42.1000000	sunset or sun -0.8 deg
10.00000	34.00000	1.41000	57.55	.167	2.1164	27.89	2.9200000	sun -4 deg
1.00000	3.40000	.25400	10.37	.269	.4590	6.05	.3160000	sun -6 deg
.10000	.34000	.06530	2.67	.432	.1499	1.98	.0325000	sun -8 deg
.01000	.03400	.02890	1.18	.603	.0812	1.07	.0043000	full moon or sun -10 deg
.00100	.00340	.02450	1.00	.699	.0759	1.00	.0003920	half moon or sun -13 deg
.00010	.00034	.02450	1.00		.0759	1.00	.0000605	starlight + sun >= -18
.00005	.00016	.02450	1.00		.0759	1.00	.0000280	midnight sun -90 deg
.00001	.00003	.02450	1.00		.0759	1.00	.0000061	overcast starlight

Figure 1.

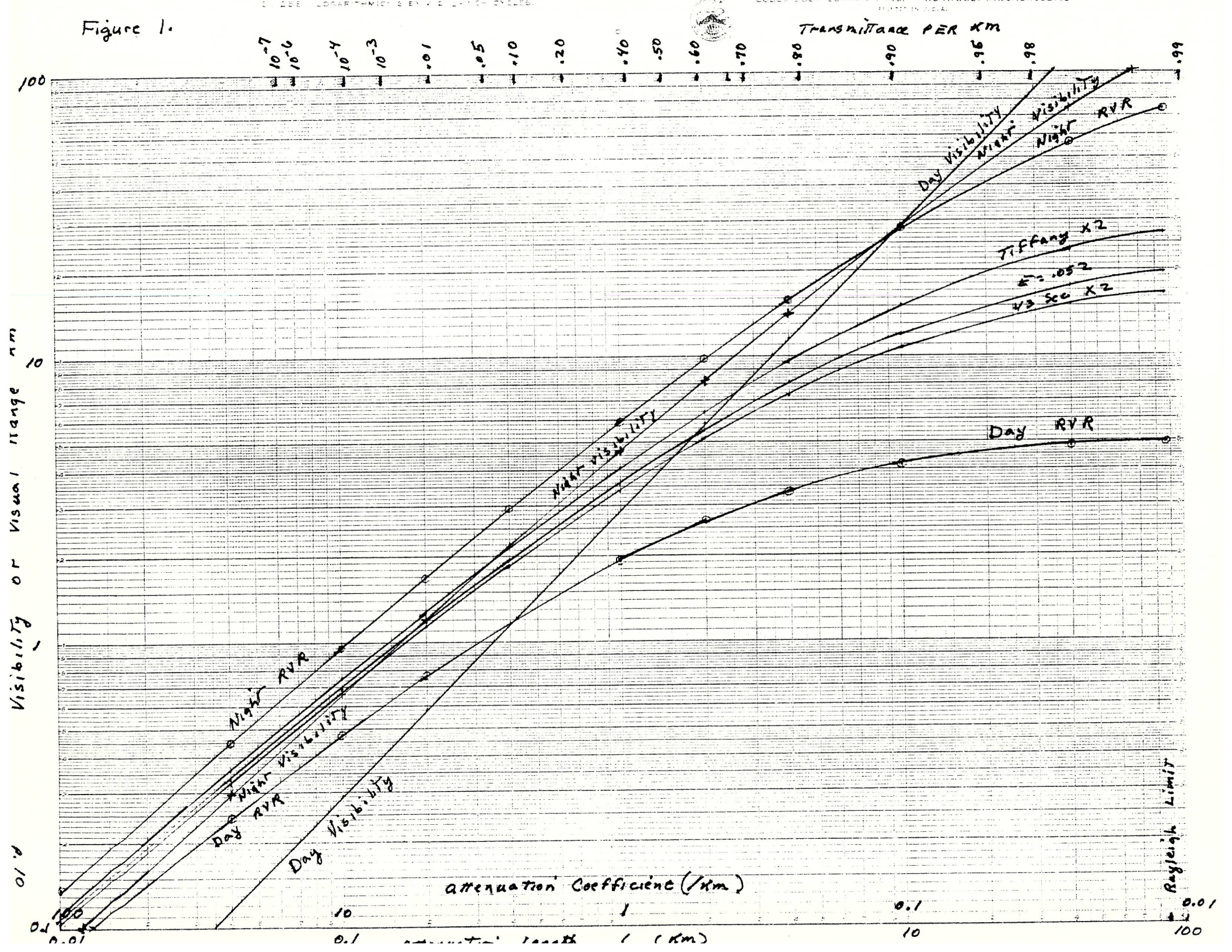
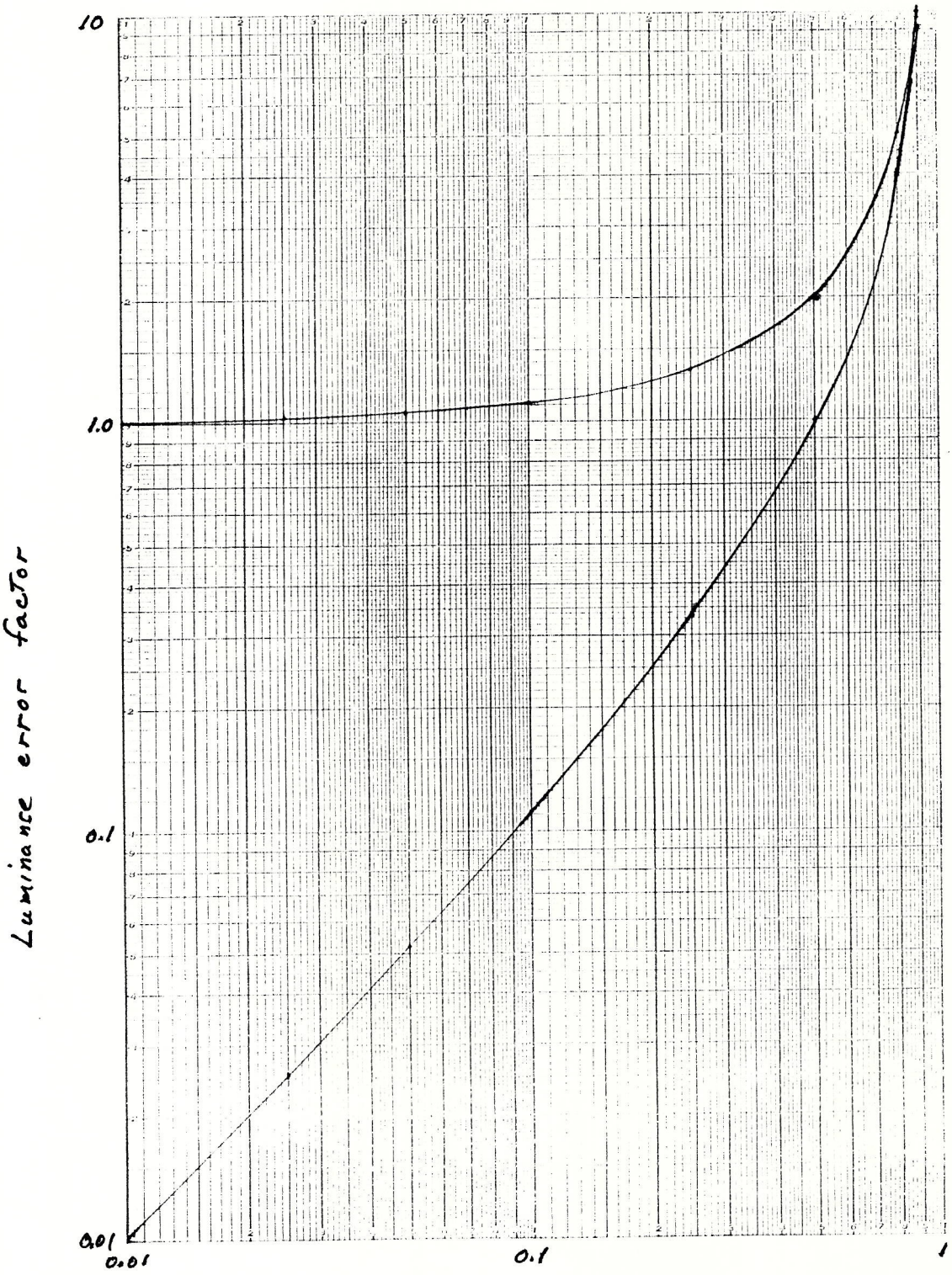

Transmittance PER Km
10^{-7}
10^{-6}
10^{-4}
10^{-3}
.01
.05
.10
.20
.40
.50
.60
.70
.80
.90
.95
.98
.99
100
10
1
0.1
0.01
Visibility or Visual range Km
Day Visibility
Night Visibility
Night RVR
Tiffany X2
$\bar{\epsilon}$ = .05 X2
1/3 Sec X2
Day RVR
Night Visibility
Night RVR
Day RVR
Day Visibility
attenuation Coefficient (/Km)
Rayleigh Limit
0.01
100
10
1
0.1
0.01
0.1
10
100

Figure 2. Luminance error factors.



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Tabe A1 Visibility and Runway Visual Range

Attenuation Length KM	Attenuation Coefficient alpha/km	Attenuation Coefficient alpha/m	T = .055 DAY Visibility km	E=IT/R I = 25 cd E = .052 NIGHT Visibility km	Range for E = I T/(R*R) I = 25 cd E = .0245 TIFFANY Range km	I = 25 cd E = .052 E=LU/SQKM Range km	I = 25 cd E = .0759 1/3 SEC Range km
.0100	100.0000	.1000000	.0290042	.0863	.1129	.107	.1034
.0400	25.0000	.0250000	.1160169	.2960	.3590	.335	.3225
.1000	10.0000	.0100000	.2900422	.6600	.7500	.692	.6620
.2000	5.0000	.0050000	.5800844	1.2000	1.2850	1.171	1.1150
.4000	2.5000	.0025000	1.1601688	2.1600	2.1550	1.940	1.8350
1.0000	1.0000	.0010000	2.9004221	4.6400	4.1000	3.610	3.3700
2.0000	.5000	.0005000	5.8008442	8.1500	6.4100	5.530	5.0900
4.0000	.2500	.0002500	11.6016884	14.1000	9.6000	8.050	7.3000
10.0000	.1000	.0001000	29.0042209	28.3000	15.0500	12.000	10.6500
40.0000	.0250	.0000250	116.0168837	74.5000	23.7000	17.600	15.1000
86.9565	.0115	.0000115	252.2106168	120.0000	27.3500	19.600	16.5000

Attenuation Length km	Attenuation Coefficient alpha/km	I = 10,000 cd E = 386 DAY Runway Visual Range km	I = 10,000 cd E = .772 NIGHT Runway Visual Range km
.0100	100.0000	.0825000	.1347000
.0400	25.0000	.2430000	.4440000
.1000	10.0000	.4750000	.9560000
.2000	5.0000	.7600000	1.6850000
.4000	2.5000	1.1750000	2.9300000
1.0000	1.0000	1.9300000	5.9100000
2.0000	.5000	2.6400000	9.8000000
4.0000	.2500	3.3500000	15.8000000
10.0000	.1000	4.1500000	28.0000000
40.0000	.0250	4.8000000	56.3000000
86.9565	.0115	4.9500000	74.5000000

Table A2 Luminance error factors

target	background	background /target ratio	Target error Factor	Background error Factor
1	.9900	.9900	100.0000	99.0000
1	.9000	.9000	10.0000	9.0000
1	.8000	.8000	5.0000	4.0000
1	.5000	.5000	2.0000	1.0000
1	.2500	.2500	1.3333	.3333
1	.1000	.1000	1.1111	.1111
1	.0500	.0500	1.0526	.0526
1	.0250	.0250	1.0256	.0256
1	.0100	.0100	1.0101	.0101

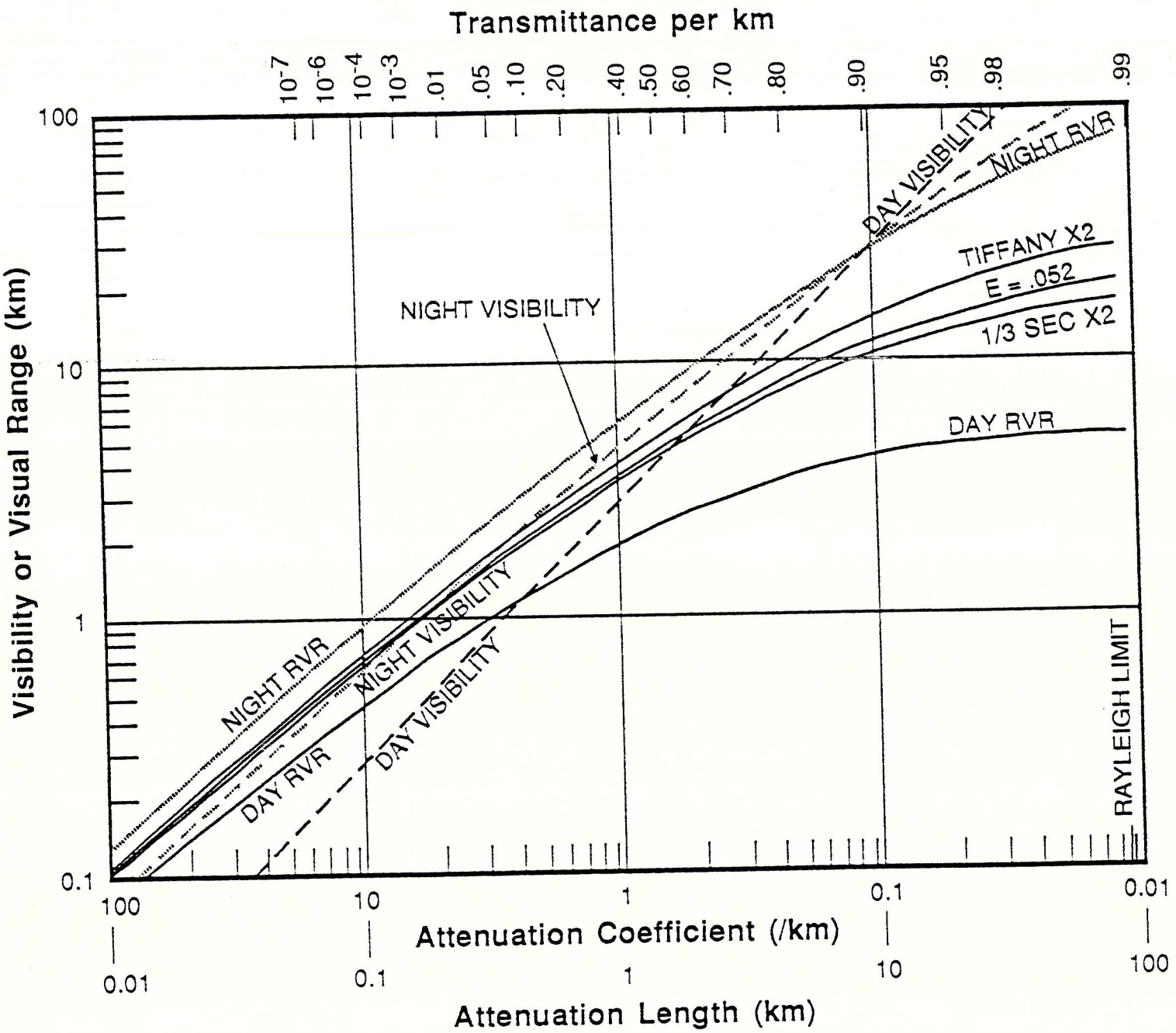
Transmittance per km
10^{-7}
10^{-6}
10^{-4}
10^{-3}
.01
.05
.10
.20
.40
.50
.60
.70
.80
.90
.95
.98
.99
100
10
1
0.1
Visibility or Visual Range (km)
DAY VISIBILITY
NIGHT RVR
TIFFANY X2
E = .052
1/3 SEC X2
NIGHT VISIBILITY
DAY RVR
NIGHT RVR
NIGHT VISIBILITY
DAY RVR
DAY VISIBILITY
RAYLEIGH LIMIT
100
10
1
0.1
0.01
Attenuation Coefficient (/km)
0.01
0.1
1
10
100
Attenuation Length (km)

Figure 1

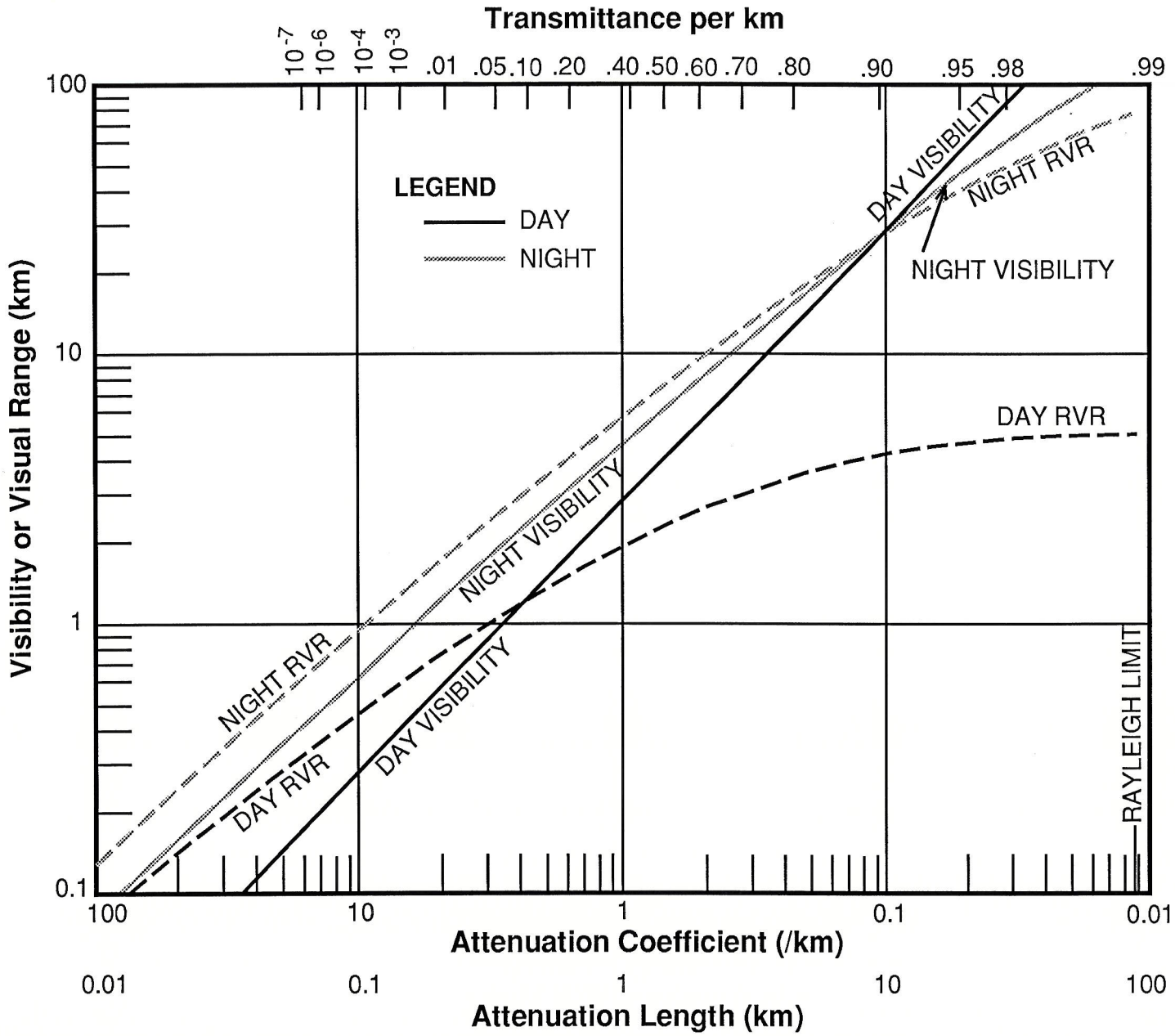
Transmittance per km
10-7
10-6
10-4
10-3
.01
.05
.10
.20
.40
.50
.60
.70
.80
.90
.95
.98
.99
LEGEND
DAY
NIGHT
DAY VISIBILITY
NIGHT RVR
NIGHT VISIBILITY
DAY RVR
NIGHT VISIBILITY
NIGHT RVR
DAY RVR
DAY VISIBILITY
RAYLEIGH LIMIT
Visibility or Visual Range (km)
100
10
1
0.1
100
10
1
0.1
0.01
Attenuation Coefficient (/km)
0.01
0.1
1
10
100
Attenuation Length (km)

Figure 1a.

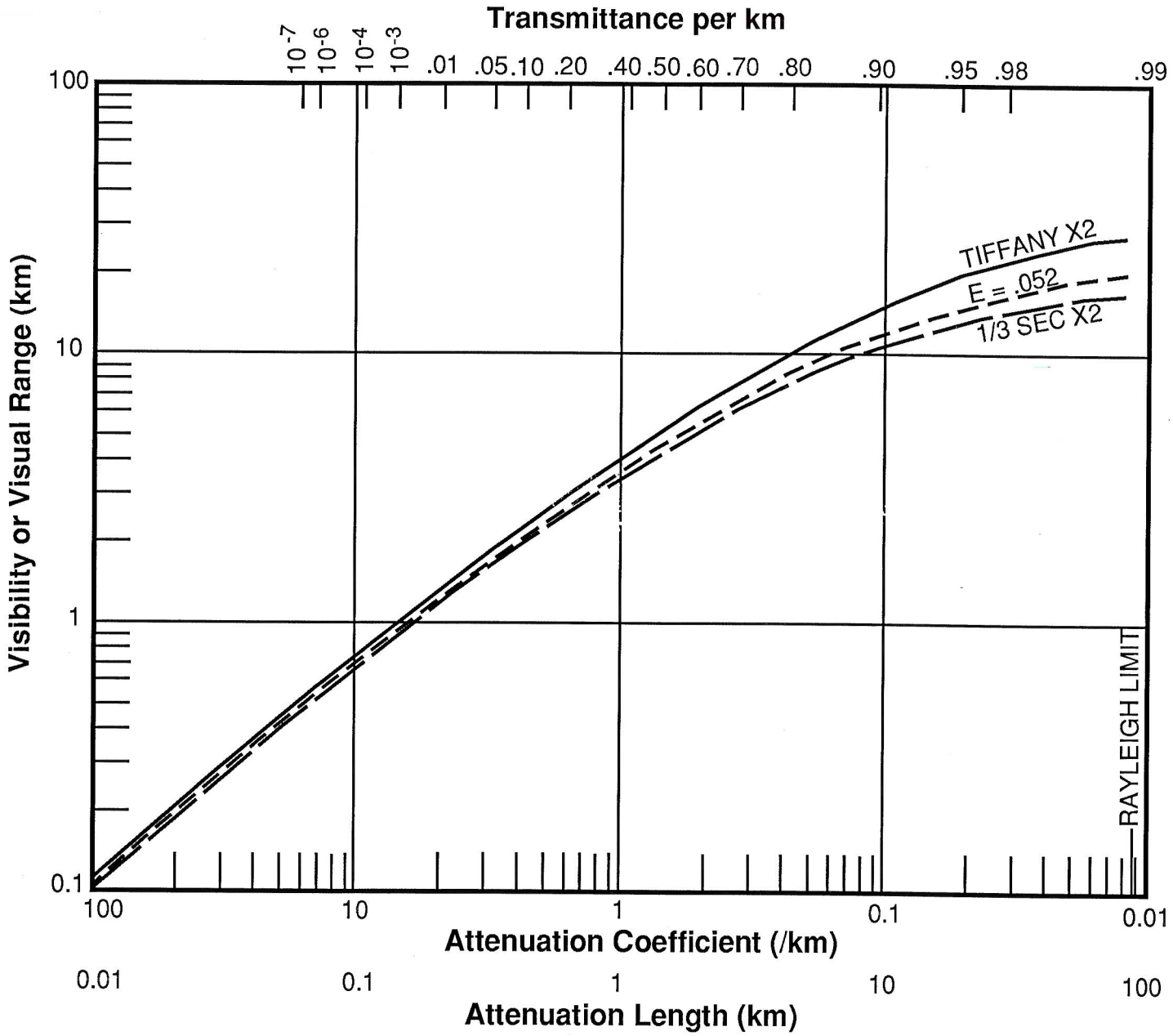
Transmittance per km
10-7
10-6
10-4
10-3
.01
.05
.10
.20
.40
.50
.60
.70
.80
.90
.95
.98
.99
100
10
1
0.1
Visibility or Visual Range (km)
TIFFANY X2
E = .052
1/3 SEC X2
RAYLEIGH LIMIT
100
10
1
0.1
0.01
Attenuation Coefficient (/km)
0.01
0.1
1
10
100
Attenuation Length (km)

Figure 1b.