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Technical Memoranda

THE DEVELOPMENT OF A PROTOTYPE AMBIENT LIGHT SENSOR FOR USE IN THE RUNWAY VISUAL RANGE SYSTEM

by

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ABSTRACT

This technical memorandum describes the development of a prototype ambient light sensor for use in the runway visual range (RVR) system. We review the definition and the computation of RVR. We compare the values of the ambient light related RVR parameters used in Canada with those used by other nations. The advantage of a continuous or multi-level ambient light measurement is considered. The results of laboratory and field tests of photovoltaic cells and photoresistors are compared with the basic sensor performance requirements for such continuous or multi-level light measurements. A circuit using a photoresistor as detector was constructed, calibrated and installed for evaluation at Toronto International Airport.

DEVELOPPEMENT DU PROTOTYPE D'UN DETECTEUR DE LA LUMIERE AMBIANTE POUR LE SYSTEME DE MESURE DE LA PORTEE VISUELLE DE PISTE

par

Brian Sheppard

RESUME

Le présent mémoire technique décrit le développement du prototype de détecteur de la lumière ambiante pour le système de mesure de la portée visuelle de piste (PVP). L'auteur rappelle la définition et le calcul de la PVP. Il compare les valeurs des paramètres de la PVP qui se rapportent à la lumière ambiante en usage au Canada aux paramètres en usage dans d'autres nations. Il étudie les avantages qu'il y a à faire des mesures continues ou à plusieurs niveaux de la lumière ambiante et compare les résultats des essais en laboratoire et en service réel des photopiles et des photorésistances au rendement minimal exigé des détecteurs pour ces mesures continues ou à plusieurs niveaux. Un circuit dans lequel le détecteur est une photorésistance a été construit, étalonné et installé pour évaluation à l'aéroport international de Toronto.

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THE DEVELOPMENT OF A PROTOTYPE AMBIENT LIGHT SENSOR FOR USE IN THE RUNWAY VISUAL RANGE SYSTEM

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Objective

The objective of this investigation is the development of a prototype sensor of ambient light with a continuous or multi-level output suitable for the derivation of runway visual range by computer.

1. Introduction

(a) Runway Visual Range

Runway Visual Range is defined by Section 16.5.1 of the WMO Guide(1) as "the maximum distance in the direction of take-off or landing at which the runway, or specified lights or markers delineating it, can be seen from a position above a specified point on its centre line at a height corresponding to the average eye-level of pilots at touchdown".

Pilots visually locate a runway by either the detection of contrast in luminance of the runway markings and the runway surface, or the detection of illumination from the runway lights. The most effective of these two methods, i.e. the one that extends the visual range the farthest, depends on a complex function of not only the ambient illumination but also the runway light intensities and the atmospheric transmissivity. For good visibility conditions, we expect the transition from contrast detection to runway light intensity detection to occur during twilight hours, although heavy overcast may reduce the general illumination sufficiently to cause this transition during the daytime also. Under poor visibilities, runway light detection may be more effective than contrast detection even for illumination levels well above those experienced at twilight.

(b) The Computation of Runway Visual Range

The RVR is computed from sensor measurements of the atmospheric transmissivity and the ambient light level, and the value of the runway lamp intensity. It is calculated using the two formulae specified by Sections 16.5.4n and 16.5.4c of the WMO

Guide (1) and given in Equations 1 and 2 below. The greater of the two calculated values is defined as the RVR.

The equation for the determination of RVR by contrasting a target with its background is a simplified expression of Koschmieder's law, given as:

$$\varepsilon = T^{V/a} \tag{1}$$

where ε is the "brightness contrast threshold", a dimensionless number defined in Appendix A, and T is the atmospheric transmissivity measured as a percentage over a baseline of length a, and V is the runway visual range determined by contrast. The basic Koschmieder theory and simplifying assumptions used to obtain Equation 1 are described in Appendix B. This simplified equation states that the contrast ratio of a target and its background deteriorates exponentially with distance. The distance at which this ratio equals the defined brightness contrast threshold for the observer is the maximum distance at which the target can be resolved against its background.

The equation for the determination of RVR by sighting runway lamps is an expression of Allard's Law:

$$E_t = \frac{I\,T^{R/a}}{R^2} \tag{2}$$

where E_t is the "illumination threshold" of the observer's eye, defined in Appendix A, I is the effective intensity, (defined in Appendix C), of the centre line or edge lights toward the observer R is the runway visual range determined by runway light detection, T and a are as defined in Equation 1 above.

Allard's law is similar in principle to Koschmieder's law except it deals with the reduction of intensity from a point light source rather than the reduction of contrast between an areal target and its background. It states that the intensity from a point light source decreases expontially with distance, but because it is a point, not an areal source, it also obeys the inverse square law. The distance at which the illumination, (defined in Appendix C), has decreased to the "illumination threshold" of the eye for the observer, is the maximum distance at which the runway light can be detected.

Assuming the adequacy of these two equations, the RVR can be computed once the atmospheric transmissivity is measured, the runway lamp intensity in the direction of the observer is known, and appropriate values are assigned to the brightness contrast threshold and the illumination threshold. The values of these last two parameters are functions of the history of the exposure of the observer's eye to light as described in Appendix A. We measure some ambient light parameter or parameters in an attempt to establish this history.

International practice has eliminated any dependence on ambient light measurements from the calculation of RVR using the contrast Equation 1, by simply assigning a fixed value to the brightness contrast threshold. The International Civil Aviation Organization (ICAO), in reference 2, recommends the value 0.05. This value is the standard currently accepted in most countries except in Canada and the United States where 0.055 is used. In practice it is immaterial which value (0.055) or 0.05 is used, since the RVR calculated in North America is only 3.2% lower than the RVR calculated from the ICAO recommended value, providing equivalent transmissivities and baselines are assumed.

ICAO (2) also recommends values for the illumination thresholds over the entire range of ambient background luminances (Figure 1). Therefore, according to international practice the calculation of RVR based on Allard's Law (Equation 2) is dependent on ambient light measurements.

(c) Empirical Relationships Between the Illumination Threshold and the Adaptation Level

The illumination threshold is the minimum illumination necessary to stimulate a brightness sensation (c. f. Appendix A). Its value depends on the luminance level to which the eye has fully adapted, referred to here as the "adaptation level". It is difficult in practice to measure this luminance, so it is frequently assumed that a measurement of the luminance of the background of a visibility target is a good estimate of the adaptation level. This is only true if the background is both uniform and extensive, and the eye has had time to adapt. In this paper we shall distinguish between the terms background luminance and adaptation level where appropriate.

The empirical relationship between the illumination threshold and adaptation level established by Blackwell (4) in 1946 is based on the largest data sample of all researchers. In his experiment, observers were given unlimited time to search for various sized fixed stimuli brighter than their background. The contrast brightness

threshold as a function of adaptation level is defined by Blackwell as the contrast ratio of a target with a 50% probability of detection against the specified background luminance.

As Figure 1 shows, the ICAO values are derived from Blackwell's relationship. However, recent results from flying operations such as those of the Blind Landing Experimental Unit (BLEU) of the Royal Aircraft Establishment of the United Kingdom (5) and simulated flying operations of the Federal Aviation Agency of the United States (6) are more pertinent to the determination of the visual range of a pilot while landing an aircraft. The BLEU data is based on a detection probability of 95%, and the FAA data on a probability of 84%. These three empirical relationships are plotted in Figure 1 along with the ICAO function and a second BLEU curve revised by Johnson (5).

(d) Comparison of the Illumination Threshold Levels Used by Several Countries

Figure 2 again shows the continuous ICAO function relating the illumination threshold of the eye and luminance of the background of the visibility target, and the step-wise approximations adopted by several other countries for RVR computations. The "Skopolog"[1] RVR system operating at some airports in Switzerland, Italy and Spain used the continuous ICAO relationship.

The vertical axis on the left-hand side of the graph gives the illumination threshold of the eye measured in lux (lumens-per-square metre). This is the parameter E required for the calculation of RVR based on Allard's Law (Equation 2). The horizontal axis at the bottom of the graph specifies the range of the background luminance levels in candles per square metre for which each country applied these threshold levels. Each illumination threshold level is labelled with the initials of the countries using it. If the luminance at which the threshold level changes is different for the various countries, it is also labelled.

Canada, the United States and Japan use the two level thresholds represented by the dashed line. The upper level, referred to as the "Day" illumination threshold is 1000 mi-cd (3.9×10^{-4} lux) and the lower "Night" illumination threshold is 2 mi-cd ($10^{-6.1}$ lux). For the purpose of comparison with the European values in Figure 2,

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[1] The Skopolog RVR system is manufactured by Impulsphysik, Hamburg.

the North American Illuminance threshold values have been converted from mile - candles to lux using the relationship 1 mi-cd = 3.86×10^{-7} lux. In practice, in these countries, switching between these illuminance threshold levels is controlled by measurements of diffuse radiation from the total sky and sun (illumination in foot-candles), rather than the brightness of part of the sky (luminance in candles per square metre) as in Europe. The North American switching level of 4 ft-c is equivalent to the illumination from the entire sky (less direct solar radiation) of a uniform brightness of 14 cd/m^2. For an explanation of the photometric units involved refer to Appendix C.

Denmark and the Netherlands also use a two level approach with a less conservative change-over luminance and daytime threshold values than North America and Japan. By conservative we mean that computations using that particular step-wise approximation to the ICAO relationship will give a lower RVR value than some other approximation.

France and Germany use a four level system, all with slight variations either in the illumination threshold levels or the background luminance change-over points. The labels "Bright Day", "Normal Day", "Intermediate" and "Night" are commonly applied to the four levels in such a system.

The U.K. uses a 32 level system (9), for which detailed information is not available.

Most countries agree to use an illumination threshold for "night" vision between $10^{-6.0}$ and $10^{-6.3}$ lux. Night is defined as beginning when the background luminance falls below a level usually between 14 and 50 cd/m^2.

(e) The Canadian RVR Illuminometer

At the present time, Canada uses a simple "day-night" switch to select one of two illumination threshold levels for the RVR computation. This sensor is manufactured commercially under the name "Lumumatic". The light transducing component is a photoresistor. It is in series with a resistive heater across 115 VAC. The resistance of photoresistor controls the current through the heater which then operates a thermal switch in the output (Figure 3). The switch is specified to open and close at an illuminance of 4 ft-cd, (43 lux). The sensor is covered by a plastic diffusing cap which is exposed to the entire hemispherical illumination.

(f) The Requirement for a New RVR Ambient Light Sensor

In the present Canadian RVR system there is a significant discontinuity in the computed RVR values when the day-night switch opens or closes. For a transmissivity measurement of 50% over a 600 foot baseline, the "Day" and "Night" RVR differs by about a factor of 2 for all intensity settings of the runway lamps. This is of particular importance in far north applications where during Arctic twilight the illumination may be in the range of the switching level for several hours. During these periods both the "Day" and "Night" illumination threshold values used in the RVR calculation would differ significantly from the value experienced by observers. We could eliminate or reduce this discontinuity by measuring the background luminance on a continuous or multi-level basis and determine the corresponding illumination threshold from a relationship such as given in Figure 1. Since the present switch is capable of only two levels of output, we must implement a modified or completely new RVR ambient light sensor.

2.   Necessary Performance Characteristics
        of a New Ambient Light Sensor

The following sections discuss the necessary performance characteristics of a new ambient light sensor.

(a) The Dynamic Range

The RVR is defined as the larger of the two RVR values calculated from the contrast Equation 1 and the Equation 2 based on Allard's Law. Only Allard's equation requires a measurement of background luminance for the computation of RVR. Therefore, the luminance range over which it gives larger RVR values than the contrast equation defines the required dynamic range of the sensor.

We expect Allard's Law to dominate under low luminance conditions. As the background luminance falls, the illumination threshold, E_t, decreases (c.f. Figure 1), and from Equation 2 the RVR must increase. The RVR as calculated by Equation 1 is independent of background luminance because the brightness contrast threshold has a fixed assigned value. Therefore, as twilight approaches there is luminance at which the RVR is greater for Allard's equation than the contrast equation given that the other parameters are fixed. Generally this luminance level is reached during twilight, but if the intensity of the runway lights is high enough and the transmissivity of the atmosphere low, Allard's Law may be the significant calculation for luminances as high as 10^4 cd/m^2.

Luminances in the range 10^4 to 10^5 cd/m^2, labelled "Bright Day" on Figure 2, may also be of interest in identifying such unfavourable lighting conditions as direct sunlight, glare off the runway or its surroundings, or scatter off an intervening obscurant such as fog. The effect of these high background luminances on the RVR is discussed in Appendix D.

The minimum general luminance experienced by a pilot is limited by his instrument panel lighting. This is estimated at 0.3 cd/m^2 by Thomas (9).

General luminance measurements between a lower limit of 0.3 cd/m^2 and upper limit of 10^4 to 10^5 cd/m^2 require a sensor with a dynamic range of approximately 5 decades.

(b) Spectral Response

Since we are using a physical sensor to measure a photometric parameter, the spectral response of the sensor should be similar to that of the eye (c.f. Appendix C).

(c), Temperature Effects

Ideally the output of the luminance sensor is independent of temperature. In practice, there will be some temperature co-efficient. Its value will depend on the type of light transducer employed.

There are several approaches to solving the temperature effects problem. Some of these are listed below.

1. The sensor temperature may be thermostatically controlled.

2. The sensor output may be electronically compensated for effects due to temperature changes.

3. The output value from the sensor may be corrected by calculation once the temperature coefficient and the temperature of the sensor are known.

4. Small effects may be ignored and their contribution to error in the RVR computation may be calculated. The error in RVR for a change in the illumination threshold sensitivity is a function of the RVR, the transmissivity and the baseline.

3.   Laboratory and Field Tests of Light Sensors

Two types of light transducers were tested for dynamic range and temperature coefficients in the laboratory and field. These were photovoltaic cells and photoresistors.

(a) The Photovoltaic Cell

The photovoltaic cell generates a voltage across a semi-conductor junction proportional to the logarithm of the illumination on the exposed sensing surface and independent of its area. This voltage is logarithmic with illumination only if the junction output is not electrically loaded. If the output is short-circuited, the resulting current is directly proportional to the illumination and the sensing area. For maximum dynamic range and constant sensitivity over the entire illumination range, the photocells were tested only in the logarithmic open circuit mode.

Performance Characteristics of Three Photocells

Three types of photovoltaic cells were tested. These are an International Rectifier (Sl020E4-PL) silicon cell, a Weston Model 594 selenium cell, and a Weston Model 856 selenium cell with a "Viscor" filter which effectively matches the spectral sensitivity of the cell to the standard luminosity factor of the human eye (c.f. Appendix C).

We determined the dynamic range and the effects of electrical loading on the output voltage for all three cells, and the temperature co-efficient for one of the selenium cells. The results from these tests are given in Table 1. The term "open circuit" voltage refers to measurements made with a 10 megohm input resistance voltmeter.

Outputs in this table are given for various illumination levels in lux because these were practically convenient to measure. These can be converted to the equivalent luminance (cd/m^2) of a uniformly bright sky using Equation C.5, if the contribution of direct solar radiation to the illumination is subtracted.

The dynamic range is specified in terms of the following parameters. The "clear sky" illumination is that from a 2π steradian field of view of a cloudless sky plus direct solar radiation. It is normally about 80,000 lux at noon at the time of the equinox for latitude 45°. About 70% to 80% of the total "clear sky" illumination is

direct solar radiation. The reduction of illumination caused by a moderate cloud cover is equivalent to shading the sensor from direct solar radiation.

Similarly, we measured the open circuit output voltage generated by the illumination from the entire sky at sunrise or sunset (approximately 450 lux).

Lastly, the response was measured to twilight illumination of 10 lux. This is about the day-night switching level in the present Canadian RVR system.

The output open-circuit voltage across the photocell can be compared to the logarithm of the illumination falling on it, to determine how closely the device approaches the theoretical log-linear relationship. The measurements were made using diffuse sunlight as a source and Wratten neutral density filters to establish illumination decades. The number of decades over which the log-linear relationship is maintained to within 5% and the sensitivity in millivolts per decade in this range are given in the table.

The internal resistance of a photovoltaic cell increases with decreasing illumination. This increases the loading effect of the measuring curcuit at low illumination levels and results in non-linearities.

The temperature coefficient was measured for one of the selenium cells. Its value was about one-half of the $2mV/^0C$ measured by Wysocki (12). The temperature coefficient of the silicon cell was not measured but should be similar to that of selenium (Reference 10, page 13).

Discussion of the Photocells' Characteristics
with Respect to the Requirements of Section 2

Of the three photocells tested, the Weston 594 has the greatest log-linear dynamic range of about $3\frac{1}{2}$ decades. This does not imply that these photovoltaic cells could not be used with non-uniform sensitivity over their full dynamic range, but all cells did show a considerable loss of sensitivity at the extremes of the required dynamic range (0.3 cd/m^2 to 0.3 x 10^5 cd/m^2).

Measurements of the internal electrical resistance of the photocells at the 10 lux illumination level indicated that the output

from all the cells must be measured by a device with an input resistance of several megohms. A simple voltage follower circuit using an FET input operational amplifier is recommended. (Figure 4).

The peak spectral response wavelength for silicon and selenium indicates that silicon is most sensitive in the near infrared and selenium is most sensitive in the visible. For practical purposes a selenium cell could be used without compensation, but a silicon cell would require an optical filter similar to the "VISCOR" to reproduce the luminosity factor of the eye (c.f. Appendix C). This filter would reduce the sensitivity of the cell by about one-half.

All cells would require compensation for the $1 \text{ mV/}^{\circ}\text{C}$ temperature coefficient. The output from an uncompensated photovoltaic sensor, exposed to constant illumination, would vary by 100 mV over the normal ambient temperature range in Canada. This is equivalent, in terms of the illumination threshold, to a change between the adjacent labelled levels of Figure 2.

This temperature sensitivity of the photovoltaic cells is its most serious performance weakness in satisfying the requirements for a new RVR ambient light sensor of Section 2. For this reason we tested photoresistors as an alternative photosensitive detector.

(b) The Photoresistor

The photoresistor is a semi-conductive device whose conductivity is theoretically directly proportional to the illumination on the sensitive surface. Because the energy conversion is not 100% efficient the change of conductivity with change in illumination is not one to one.

The photoresistor used in the present day-night switch is a National Semi-conductors Ltd. (NSL) No. 446 cadmium sulphide cell with a specified typical 1 ft-cd resistance of $11.4\text{k}\Omega$ and a minimum dark resistance of $12\text{M}\Omega$. We also tested a similar photoresistor, the NSL No. 443, with a specified 200 kΩ resistance at 1 ft-cd and a minimum dark resistance of $300\text{M}\Omega$. Parameter measurements for these photoresistors similar to those for the photocells are given in Table 1. For both the NSL No. 446 and 443, the slope of the transfer characteristic between the logarithm of illumination and the logarithm of resistance decreases monotonically from a value of one at low illumination levels (less than 10 lux), to a value of one-half at higher ranges (10^3 to 10^5 lux).

The temperature coefficient of photoresistors is smaller than for photovoltaic cells. No published data on the temperature coefficient of CdS could be found, but Larach (11) states that for CdS:I:Cu, it is dependent on both temperature and light intensity. Our tests showed that the resistance of the NSL No. 443 CdS photoresistor decreased by 8% over the temperature range $22^{\circ}C$ to $-40^{\circ}C$ at an illumination of 20 lux and decreased by 4% at an illumination of 5,500 lux.

The sensitivity of the cadmium sulphide cell is centred in the green wavelengths of the visible spectrum (11), and approximately matches the response of the eye.

The Photoresistor in an Ohmmeter Measuring Circuit

A photoresistor could be used in series with a resistor across a constant voltage supply in an "ohmmeter" type measuring circuit (Figure 5). The family of curves in Figure 6 show the relationship between the output voltage scross the fixed series resistor, expressed as a percentage of the constant voltage supply, and the resistance of the NSL-446 photoresistor given across the top horizontal axis of the graph. The family of curves are parameterized by the value of the fixed series resistor (R_s) labelling each curve. The shape of each member of the family is identical.

The illumination in lux, is scaled on the lower horizontal axis to correspond to the resistances on the upper axis. Below this the luminance axis in candles per square metre is derived from Equation C.5 of Appendix C. The correspondence between illumination and luminance assumes a sky of uniform brightness.

The labels "Bright", "Normal Day", and "Intermediate" above the lower horizontal axis, are the background luminacnes at which the illumination threshold changes to the level with the corresponding label on the right vertical axis on the graph of Figure 2. The label "D/N" is the illumination level at which the North American "day-night" switch is specified to operate.

For each curve the 10% and 90% voltage points are separated by two decades of resistance. By selecting an appropriate series resistor value we can adjust the location of the dynamic range on the luminance axis. This can be shifted by a factor equivalent in sign and magnitude to the change in the series resistance.

Below the 10% and above the 90% voltage output levels, the curves asymptotically approach the 0% and 100% limits. The maximum sensitivity is at the 50% level where the series resistor and photoresistor have equal values. At the 10% and 90% levels, the log-log sensitivity is about $\frac{1}{2}$ of this maximum for all values of series resistors. If the 10% and 90% voltage output levels define the limits of the dynamic range, then for practical values of the series resistor the range of the NSL 446 photoresistor in an ohmmeter type measuring circuit is approximately two decades of luminance.

The day-night" switch uses a 6.8 kΩ series resistor (Figure 3). The 6.8 kΩ curve is plotted in Figure 6 to show the sensitivity of the "day-night" switch at its change-over luminance level of about 14 cd/m^2. As applied here, it is close to the optimum sensitivity.

The disadvantage of the ohmmeter type photoresistor circuit is its limited dynamic range. Error can be introduced at the upper end of the scale by drift in the constant voltage supply. A change of 5% in supply voltage is equivalent to 3 decades change in illumination at the highest light levels. Offset errors in the A to D converter (Figure 5) would cause errors at the lower end of the dynamic range. An offset of 1% in the A to D converter is equivalent to $\frac{1}{2}$ decade change in illumination at low light levels.

The Photoresistor in a Current Controller Oscillator Circuit

A second possible photoresistor sensor circuit is a current controlled oscillator circuit (Figure 7) similar to that used in the transmissometer receiver. This circuit produces a frequency proportional to the resistance of the photoresistor located in the feedback loop of the oscillator.

The circuit charges the capacitor at a rate controlled by the resistance of the photoresistor Rp and the feedback voltage, V_f. When the capacitor voltage V_c, equals the comparator voltage V_{comp}, at the non-inverting input of the first stage of the 1458 operational amplifier, the output voltage of the last stage of the 1458 changes polarity, as does the comparator voltage through the resistor divider R_1 and R_2. At this time, the capacitor charges towards this new comparator voltage.

The sensitivity of the system can be controlled in several ways. The size of the capacitor and the voltage comparator level determine how much current is required for one charging period. The level is set by the ratio of resistances R_1 to R_2. The photoresistor resistance and charging voltage at the output of the second

stage of the 1458 determine the rate of charging. The value of the gain of this last stage, set by potentiometer R_3, controls this voltage as a firm ratio with the comparator voltage.

This measuring circuit limits only the upper end of the dynamic range. When the photoresistor resistance falls below a certain value at high illumination levels, the 740 operational amplifier can no longer supply the necessary capacitor charging current. Such would be the case for the "clear sky" resistance (c.f. Table 1), of the NSL 446 used in the "day-night" switch. For this reason we have also tested the higher resistance NSL 443 photoresistor. This sensor reduces the capacitive charging current by a factor of ten at clear sky illumination levels.

The output frequency is directly proportional to the photoresistor's resistance. Therefore, unlike the ohmmeter circuit, this circuit has the advantage of constant sensitivity over the full dynamic range and insensitivity to offset errors in amplifiers and drifting of the reference voltages. In the ohmmeter measuring circuit, the circuit characteristics limited the useful dynamic range of the sensor. With the current controlled oscillator circuit, this is not a restriction. The measuring circuit can be designed to have a dynamic range exceeding that of the sensor. The output frequency range for any luminance range is easily shifted by adjusting potentiometer R_3.

A photoresistor in a current controlled oscillator circuit has a significantly lower temperature coefficient than a photovoltaic cell and may in fact require no temperature compensation over the normal ambient range.

A further advantage of the photoresistor in the current controlled oscillator circuit is that the signal can be transmitted from the site to the RVR computer using the same telemetry techniques as the transmissometer signal. This could simplify the handling of the sensor data for the RVR computation.

4.   The Status of this Development

We have constructed the prototype current-controlled oscillator circuit given in Figure 7 using the NSL 443 photoresistor. We removed the thermal switch from a "Lumamatic" day-night switch, described in Section 1 e, and mounted the new circuit under the plastic diffusing cap so that the new photoresistor assumed the same horizontal position as the old one. This sensor was installed outside the Meteorological Observer's office at the Toronto International Airport. Its feild of view includes the entire hemisphere so that it measures total illumination from direct solar radiation and sky light.

The sensor was calibrated against a standard Eppley illuminometer over four decades of illumination (c.f. Figure 9). The lowest illumination decade (dashed part of curve) is extrapolated. In practice the illuminometer pulses are averaged over one minute. The output is recorded by the meteorological observer before and after his routine observations. The outputs from several scatter-type visibility meters and the observer's prevailing visibility estimate are also simultaneously recorded.

5.   Conclusions

A prototype sensor of ambient illumination with a continuously variable frequency output suitable for the computation of runway visual range has been designed and constructed to measure five decades of ambient illumination over the normal range of ambient temperature in Canada. We are testing the sensor in the field to verify that its performance meets the requirements of the R system for such a measurement.

APPROVED,

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APPENDIX A

Definition of the Brightness[1] Contrast and Illumination
Thresholds for the Human Visual System

The eye is a light sensor whose output is the brightness sensation and whose input is the irradiance[1] from the energy source. The eye's performance characteristics depend on the level of luminance[1] to which it has adapted. We call this the adaptation level (c.f. Section 1c). When the eyes have become adapted to a luminance greater than 3 cd/m^2, retina response is due to stimulation of its cones. This is called "photopic vision". At luminance levels less than 3×10^{-5} cd/m^2 only the retinal rods are sensitive. This is called "scotopic vision".

The response of the eye is approximately logarithmic with incident illuminance[1] except at the extreme limits of the dynamic range which are determined by the adaptation level. This is a specific application of Weber's Law as described by Guilford (12). The upper limit of the dynamic range is the luminance level at which the retina becomes dazzled. The lower limit is the "illumination threshold", introduced in Section 1a, and defined as the smallest illuminance required to stimulate the brightness sensation.

Blackwell's paper on <u>Contrast Thresholds of the Human Eye</u> (3) explains the experimental procedure used to measure the brightness contrast threshold as a function of background luminance. He introduces concepts which will aid in the understanding of the following definition of brightness contrast threshold.

The smallest absolute difference between two luminance stimuli, B_0 and $B_0 \pm \Delta B$ which causes a distinguishable brightness response is known as the "difference limen", ΔB. Since the eye is a logarithmic sensor, this parameter is dependent on B_0 and on the adaptation level. For this reason, it is not a particularly useful parameter and the sensitivity of the eye to contrast is most commonly described by a photometric parameter called the "brightness contrast threshold", ε, also introduced in Section 1a. This is the ratio of the difference limen, ΔB, to B_0. Therefore:

$$\varepsilon = \frac{\Delta B}{B_0}$$

A.1

In the meteorological case, the luminance of the background of the visibility target frequently determines the adaptation level.

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[1]The reader should refer to Appendix C for an explanation of the radiometric and photometric parameters used in this Appendix.

APPENDIX B

The Formulation of Visual Range

The most comprehensive presentation of this material is W. E. K. Middleton's text, Vision Through the Atmosphere (13), on which we base the following development.

For the purpose of this discussion, visual range will be defined as the maximum distance at which a target can be distinguished from its background. The background is defined as that part of the field of view immediately adjacent to the target. Detection of a target does not necessarily imply recognition or identification of the target. An object is usually recognized because it has a different colour or brightness over its surface. An object can be detected against its background by differences in brightness alone.

We shall define the luminance contrast in terms of an isolated object surrounded by a uniform and extensive background, so that the luminance of the background is equivalent to the adaptation luminance. If the luminance of the object is B and the background B', the "intrinsic luminance contrast" i.e. the photometric (c.f. Appendix C) contrast measured at the target, is defined by:

$$C = \frac{B - B'}{B'} \qquad \text{B.1}$$

The visual range for any particular observer is that distance at which the intrinsic luminance contrast of target and background is reduced by atmospheric interaction to an apparent luminance contrast equal to the brightness contrast threshold for his eye. Alternatively, if the target is a point source of light, its visual range is the distance at which the illumination from the source has decreased to the illumination threshold of the eye, as adapted to its environment.

For objects less luminous than their backgrounds, the luminous contrast is negative. The maximum negative contrast is -1 for a black object regardless of the background luminance. For objects brighter than the background the contrast is positive. Any positive value for C is possible, and very large values of C occur when viewing lights at night.

Koschmieder in 1924 is credited as the first researcher to develop a theory for calculation of visual range in the horizontal, of objects seen against the horizon sky. He derived an expression for the apparent

brightness of a black object seen at a distance . His mathematical model of the atmosphere is based on the following physical assumptions:

1. The atmosphere is a turbid medium, containing a large number of small particles.

2. Although there are a large number of particles, they have a small volume density.

3. The scattering action of each particle is independent of the presence of all the others.

4. The scattered light from an element of volume is incoherent. The intensity from an element of volume is proportional to the number of particles.

5. Atmospheric refraction is neglected.

6. All parts of the atmosphere in a horizontal plane are equally illuminated.

7. The coefficient of attenuation by scattering is constant in the horizontal plane.

8. The earth's surface is a horizontal and diffusely reflecting plane.

9. The linear dimensions of the target are small in comparison to its distance from the observer.

As applied to the computation of runway visual range, the most restrictive of Koschmieder's assumptions is number 7. However, as we shall see in Appendix D, in certain instances, this is not as serious a simplification as those made in the reduction of the basic visual range Equation B.4 to the contrast RVR Equation 1 .

Koschmieder's theory has been re-developed by succeeding investigators using different approaches. We shall follow Middleton's development. The "intrinsic" luminances and contrast ratios shall be subscripted with a "0" indicating they are measured at zero distance from the target. "Apparent" luminances and contrast ratios are subscripted with a "r" indicating they are measured at a distance r from the target. This apparent luminance will change with distance due to two atmospheric phenomena: B_0 is diminished by atmospheric extinction caused by scattering and absorption of light originating from the object and, B_0 is increased by scattering of light from all parts of the

sky and ground into the optical path between the object and the viewer. This is generally equal for both the target and its immediate background. Therefore, any expression for the difference in luminance between the background and the target when viewed at any distance, is not influenced by "air-light" luminance. Only the extinction factor remains. It is given from Beer's Law that:

$$(B - B')_r = (B - B')_0 \left(e^{-\sigma(r)r} \right) \qquad \text{B.2}$$

where $\sigma(r)$ is the extinction coefficient over the line of sight of distance r.

If we are dealing with horizontal visibility through an atmosphere modelled on Koschmieder's assumptions, then we can say that $\sigma(r)$ is a constant σ_H. Visibility not in a homogeneous horizontal plane sometimes referred to as "slant visibility" may be calculated using a single value of the extinction coefficient, σ_W, which has been weighted over the line of sight. This is usually a difficult measurement.

Converting to contrast ratios, from Equation B.2 we see that:

$$\left(\frac{B - B'}{B'} \right)_r = \left(\frac{B_0'}{B_r'} \right) \left(\frac{B - B'}{B'} \right)_0 \left(e^{-\sigma_H r} \right) \qquad \text{B.3}$$

where the background luminance may be a function of r, as when viewing objects against terrestrial background through illuminated fogs. Using Equation B.1 this may be re-written:

$$C_r = \left(\frac{B_0'}{B_r'} \right) \left(C_0 \right) \left(e^{-\sigma_H r} \right) \qquad \text{B.4}$$

Equation B.4 is Koschmieder's expression for the law of contrast reduction by the atmosphere. In applying this equation to the determination of visibility by a transmissivity measurement, instrumentation meteorologists made additional assumptions. For the RVR contrast equation the background luminance is assumed independent of distance so that $B_r' = B_0'$. Then the apparent contrast ratio decreases exponentially with distance r:

$$C_r = \left(C_0 \right) \left(e^{-\sigma_H r} \right) \qquad \text{B.5}$$

The further assumption that the object is "black", $B_0 = 0$ simplifies this equation to:

$$C_r = e^{-\sigma_H r} \qquad \text{B.6}$$

Where Equation B.4 is a general expression for horizontal visibility in a "Koschmieder" type atmosphere, the assumptions made to obtain Equations B.5 and B.6 may, in certain instances, be unacceptably restrictive when applied to the RVR problem. The pilot's target is seldom a black object viewed against the horizon. In practice, the target is the runway markings against the runway surface. In either case the assumption that the background luminance is not a function of the target distance is probably the single most significant source of inaccuracy in applying Koschmieder's theory to RVR computations. This is particularly true during poor visibility conditions when interposed illuminated fogs may increase B_r' to a level much higher than B_0' (Figure 9).

To complete the development of the RVR equation by contrast (Equation 1, section 1b) we define the transmissivity of the atmosphere, t, by the relation:

$$t = e^{-\sigma H}$$

<div align="right">B.7</div>

The transmissometer measurement T over a baseline a is defined by:

$$T = t^a$$

<div align="right">B.8</div>

Therefore, we have:

$$e^{-\sigma H} = T^{1/a}$$

<div align="right">B.9</div>

and Equation B.6 becomes:

$$C_r = T^{r/a}$$

<div align="right">B.10</div>

When C_r equals the brightness contrast threshold ϵ, then the target is just discernible and r becomes equal to V, the runway visual range by contrast. Equation B.10 is then equivalent to Equation 1 of section 1b.

APPENDIX C

An Explanation of Some Radiometric and Photometric Parameters

Radiometric parameters define functions for the quantitative measurement of electromagnetic energy radiated at all wavelengths. Photometric parameters are similar functions defined to quantitatively measure the relative potential of radiant energy, as a function of wavelength, to stimulate a psychophysical response from the human visual system. This response is called "brightness".

Brightness is a psychological concept which cannot be measured. Brightness can only be qualitatively described in the following manner: the presence or absence of the sensation and the relative magnitude of two or more sensations.

The system of photometric units attempts to quantify the response of the human visual system to radiant energy of different wavelengths. The effect of mental processes on this response is ignored. The sensitivity of a "standard retina" as a function of wavelength is called the "luminosity". The luminosity curve is sometimes normalized to unity at 556 nm, the wavelength of maximum sensitivity for photopic eye response (c.f. Appendix A), and decreases to zero for wavelengths not in the visible spectrum. The maximum in the normalized luminosity curve shifts to 511 nm for scotopic vision.

Table 2 shows some corresponding radiometric and photometric parameters with their units, symbols and defining equations.

The radiometric parameters are functions of the unit of radiant energy called the joule while the corresponding photometric parameter is the unit of luminous energy called the talbot. Flux, as used here, refers to the time rate of energy flow. For radiant energy this is measured in watts, for luminous energy in lumens. The numerical relation between corresponding radiometric and photometric quantities for a specified wavelength, equal the luminosity and is typically expressed in lumens per watt.

The radiometric parameter for the intensity of an energy source in a particular direction is the radiant intensity. This parameter is a measure of the power radiated into a unit solid angle centred on the source and oriented in the direction of interest. Its units are watts per steradian. The corresponding photometric unit is the luminous intensity (I), and is measured in candelas. The candela was defined in 1948 for the purpose of establishing a reproducable intensity standard. It replaces an older unit called the candle. For most practical purposes, these units are equal and since the candle is so firmly entrenched in the literature it will be used exclusively in this paper.

The photometric parameters of greatest interest to this paper are the illuminance and luminance. These are frequently confused and must be defined with care.

Illuminance (E) is the incident flux (dF) per elemental area (ds) of a receiver. Therefore:

$$E = \frac{dF}{ds} \qquad\qquad C.1$$

Illuminance is often called illumination when it refers to flux incident on a material surface. In metric units, illumination is measured in lumens per square metre (lm/m^2), also, called metre-candles (m-cd) or lux, and in English units, it is measured in lumens per square foot (lm/ft^2), also called foot-candles (ft-cd) or in lumens per square mile (lm/mi^2) as called mile-candles (mi-cd).

In this paper we use metric illumination units. Equation C.2 gives English equivalents for comparison:

$$\begin{aligned}
1 \text{ lux} &= 1 \text{ } lm/m^2 = 1 \text{ m-cd} \\
&= 0.0929 \text{ } lm/ft^2 = 0.0929 \text{ ft-cd} \\
&= 2.59 \times 10^6 \text{ } lm/mi^2 = 2.59 \times 10^6 \text{ mi-cd}
\end{aligned}$$

The luminance of a source in a given direction, sometimes referred to as the "brightness" (B) of the source, is the ratio of the incremental change in the illumination on a surface normal to this direction d(En) to the incremental change of the solid angle of acceptance of source illumination (dΩ), centred on this element of surface and oriented normal to it. Therefore:

$$B = \frac{d(En)}{d\Omega} \qquad\qquad C.3$$

In metric units luminance is measured in candles per square metre (cd/m^2), and in English units in candles per square foot (cd/ft^2). The conversion relation is:

$$1 \ cd/m^2 = 0.0929 \ cd/ft^2 \qquad \text{C.4}$$

It is frequently convenient for the comparison of measurements of ambient light, to be able to calculate the illumination from the sky (E), knowing the luminance of any portion and vice versa. If all parts of the sky are of uniform luminance (B), then by integration of Equation C.3 we get:

$$B = {}^{E}/_{\pi} \qquad \text{C.5}$$

In this work, we have often found it convenient to assume this condition satisfied to facilitate the conversion from English illuminance units to metric luminance units using the relationship:

$$1 \ ft\text{-}cd = 3.426 \ cd/m^2 \qquad \text{C.6}$$

Many illuminometers are cosine compensated so that all radiation falls normally on the sensing surface. Then integration of Equation C.3 gives:

$$B = {}^{E}/_{2\pi} \qquad \text{C.7}$$

APPENDIX D

Ambient Light Measurements Required for an Improved Computation of Runway Visual Range

The ambient light intensity and its distribution affects the visual range of a target as defined in Appendix B through two independent mechanisms, one physical, the other psysiological. For objects sighted by contrast, ambient light is the radiant energy source of photons required to stimulate the retina. Also the illumination threshold sensitivity of the eye is a function of the recent history of total radiant energy falling on the retina.

Koschmieder's theory is a physical development of the effects of ambient light on the reduction of luminance contrast of an areal target and its background by atmospheric absorption and scattering over the viewing path.

We may determine the physical effects of ambient light on the reduction of contrast by examining each term of Equation B.4.

The intrinsic contrast ratio of the target and its background $C_0 = \left(\dfrac{B - B'}{B'}\right)_0$, is independent of the ambient illumination assuming that it is equal on both the target and background. This factor is dependent only on the reflectivities of the surfaces concerned.

However, the ambient illumination does affect the background luminance ratio B_0'/B_r'. "Veiling", due to atmospheric scattering of light into the optical path between the observer and the background of the target, will reduce this ratio. This condition occurs when an illuminated fog is located between the observer and the target background as shown in Figure 9. The veiling effect is highly dependent on the relative positions of the fog, the sun, and the observer's line of sight.

The transmissivity term $e^{-\sigma_H r}$ in Equation B.4 is independent of ambient light.

Koschmieder's theory does not consider the physiological relationship between the history of the retina's exposure to radiant energy and its sensitivity to contrast and illumination. The most extensive experimental research into these relationships was done by Blackwell

as mentioned in Section 1c. The time available to locate the target in such experiments is an important factor as mentioned by Thomas (8) in his discussion of the findings of the Blind Landing Experiment Unit (BLEU) of the Royal Aircraft Establishment. Blackwell's observers were permitted long periods of time to search for their targets. The BLEU observers were pilots landing aircraft in fog. The pilots had a short decision time which resulted in a lower probability of the target being detected. As a result, at the lowest light levels the illumination threshold of the eye for the BLEU experiments was a factor of ten greater than Blackwell's results (c.f. Figure 1).

The international approach to the practical problems of measurement of the relevant ambient light parameters has been overly simplified. The value of the brightness contrast threshold defined as 0.05 by ICAO is overestimated to give a conservative value for the RVR. This is partially intended to compensate for inaccuracies introduced by ignoring the physical mechanisms by which ambient light affects visibility. Blackwell's data indicates that a value for the brightness contrast threshold of 0.02 or less is appropriate for targets of angular dimension $\frac{1}{2}^{\circ}$ or greater under normal daylight illumination conditions.

Application of Equation B.4 to the computation of the RVR by contrast requires a photometric measurement of the background luminances measured both at the target and the observer, in the direction of observation. In practice this is difficult because the observer is a pilot in the cockpit of an airplane and the target background is continuously varying. An estimation of the intrinsic luminance of the background, B_0', is possible from a general illumination measurement near the surface and knowledge of the reflectivity of the surface in the direction of interest. The field of view of such a measurement should include all sources, including direct sunlight, illuminating the areas of interest. For this purpose, the sensor's surface should be horizontal, located beside the runway, and have a 2π steradian field of view.

Any direct luminance measurements of the background, as seen by the pilot, would require a sensor in the cockpit of the aircraft. This is impractical. As a first approximation, a sensor located beside one end of the runway, could measure the luminance of the horizon at the opposite end in a field of view similar to that of a pilot at touchdown. This would require a duplicate sensor at the other end of the runway for take-offs and landings in the opposite direction.

With two sensors at the end of the runway one could determine the ratio between the general illumination and the background luminance of the horizon for normal ambient lighting. Departures from this ratio

would indicate the presence of such unfavourable lighting conditions in the pilot's field of view as direct sunlight, glare off the runway and surrounding terrain, or illuminated fogs.

If a measurement of the background luminance of the horizon at the end of the runway opposite touchdown is not fluctuating rapidly, it could be used as a measure of the adaptation luminance of the pilot's eye. A continuous value of the illumination threshold could be assigned from one of the relationships given in Figure 1. However, we must recognize that the pilot's eye may have adapted to a different luminance level, while on his glide path, than that measured by a ground based sensor.

TABLE 1

MEASURED CHARACTERISTICS OF THREE PHOTOVOLTAIC CELLS AND TWO PHOTORESISTORS

MEASURED PARAMETER	PHOTOVOLTAIC CELLS			PHOTORESISTORS	
	Int. Rectifier (Silicon)	Weston 594 (Selenium)	Weston 856 + "Viscor" Filter (Selenium)	NSL 446 (CdS)	NSL 443 (CdS)
Output for the following Illumination levels:	Open Circuit Voltage[1] Across Photovoltaic Cell Junction			Resistance Of the Photoresistors	
1. "Clear Sky"[2] approx. 80000 lux	540 mV	400 mV	500 mV	27 Ω	270 Ω
2. "Sunrise or Sunset" approx. 450 lux	261 mV	237 mV	190 mV	645 Ω	
3. 10 lux illumination	11 mV	53 mV	31 mV	18K Ω	120K Ω
Log-Linear Dynamic Range of Photovoltaic Cells	2 Decades	$3\frac{1}{2}$ Decades	2 Decades		
Photovoltaic Cell Sensitivity in Log-Linear Range (mV/decade of illumination)	162	100	165		
Photoresistor Sensitivity (decades of resistance/ decade of illumination).				Varies from 1 at illumination levels below 10 lux to $\frac{1}{2}$ in the range of 10^3 to 10^5 lux.	
Internal Resistance of photovoltaic cell for 10 lux illumination.	7.6K Ω	75.3K Ω	21.6K Ω		
Temperature Coefficient of Photovoltaic Cell	not measured	not measured	Approx. 1 mV/°C		
Effect of temperature variation on resistance of cadmium sulphide photoresistor at 20 lux illumination				not measured	8% decrease over 22 C to -40 C range
Peak spectral response wavelength[3]	900 nm	550 nm	550 nm	550 nm	550 nm

NOTES: 1. The Open circuit voltage is measured with a 10 M input resistance voltmeter
2. "Clear Sky" refers to direct sunlight and illumination from the entire cloudless sky.
3. For photovoltaic cells see Reference 10, p.1 and 19. For photoresistors see Reference 11, p.126.

TABLE 2

TABLE OF CORRESPONDING RADIOMETRIC AND PHOTOMETRIC PARAMETERS

RADIOMETRIC		PHOTOMETRIC				
Parameter	Metric Units	Parameter	Metric Unit	English Unit	Symbol =	Defining Equation
Radiant energy	Joule	Luminous energy	talbot	talbot	Q	
Radiant flux	watt	Luminous flux	lumen	lumen	F =	dQ/dt
Radiant intensity	(watt/Ω)*	Luminous intensity	candle †	candle	I =	$dF/d\Omega$
Irradiance	watt/m^2	Illuminance	lumen/m^2 (lux)	lumen/ft^2 (foot-candle)	E =	(dF/ds) ‡
Radiance	watt/(Ω xm^2)	Luminance	candle/m^2	candle/ft	B =	$d(En)/d\Omega$ ‡‡

* Ω is a unit of solid angle (usually the steradian) centred on the source of radiant energy,

† The candle is an old unit of luminous intensity replaced in 1948 by the candela, a more reproducable standard.

‡ ds is an element of area of the surface on which the illumination is measured.

‡‡ En is the illumination measured on an element of surface normal to the direction between the source and the point of observation. Here $d\Omega$ is an incremental change of solid angle centred on this element of surface and oriented normal to it.
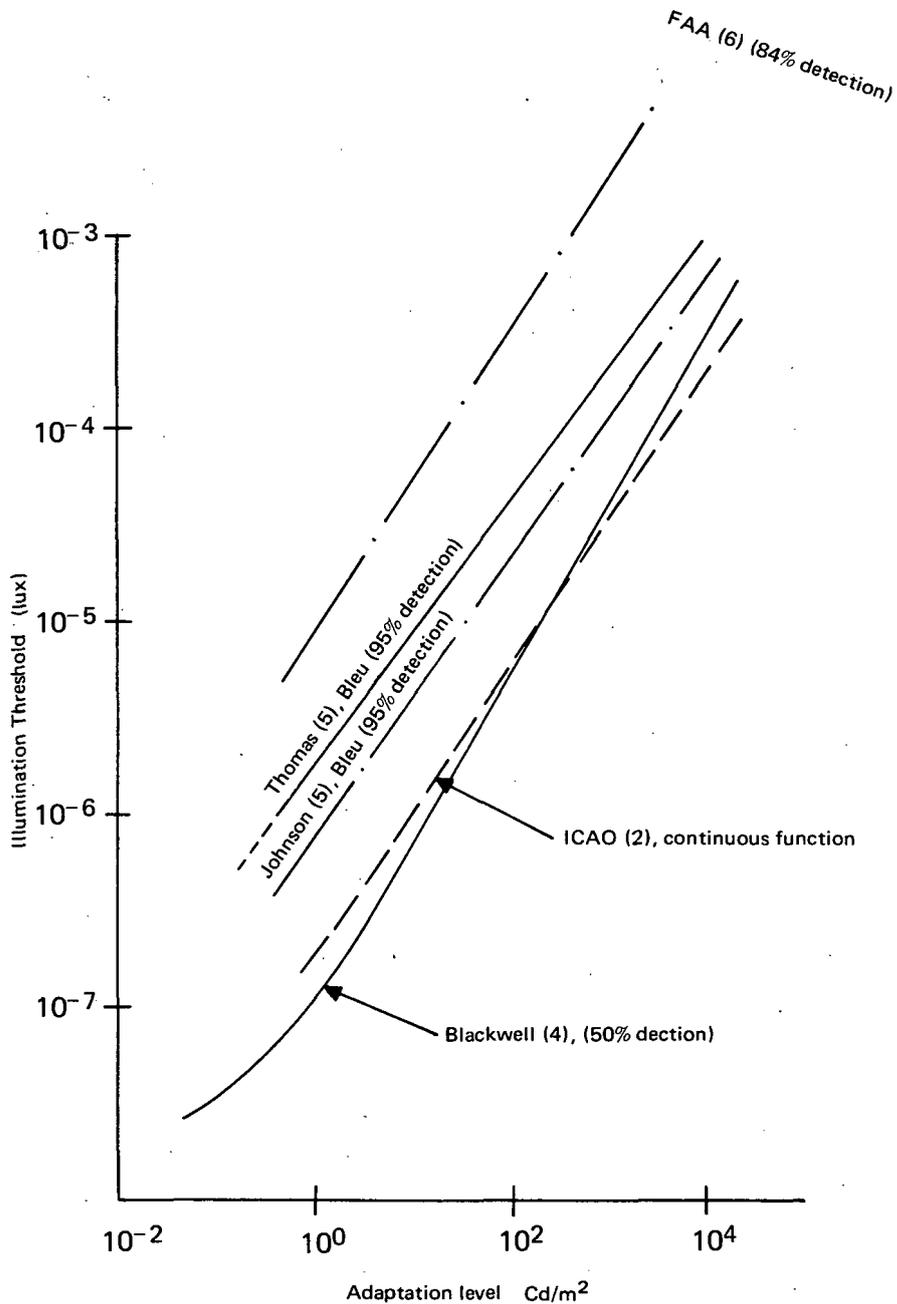
Figure 1

Several empirical relationships between the illumination
threshold of the eye and its adaptation level, as provided by Johnson (5)
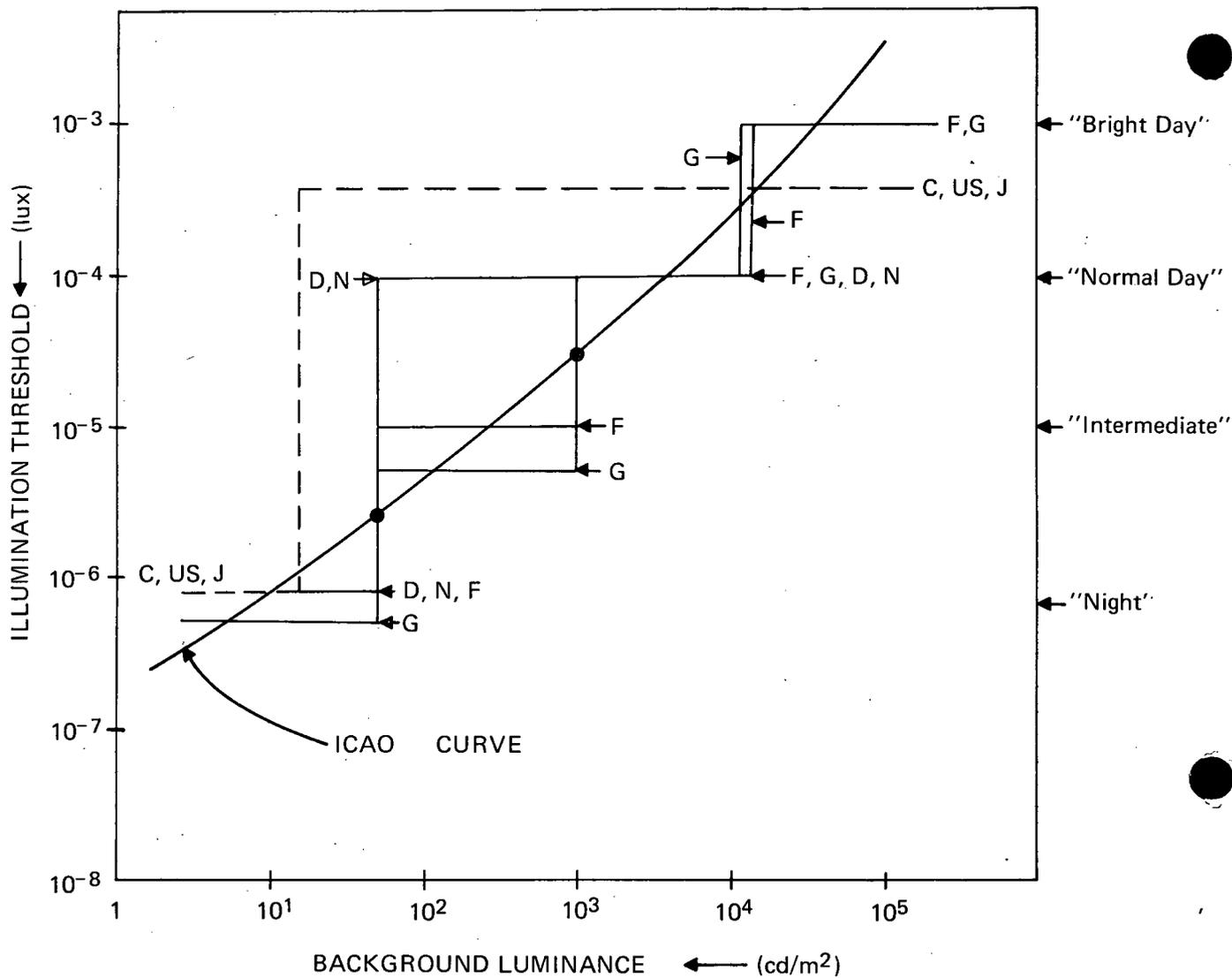
Figure 2
ICAO relationship between the illumination threshold and the
luminance of the background of the target. The setp-wise
approximations adopted by several countries for
RVR computations are shown for comparison
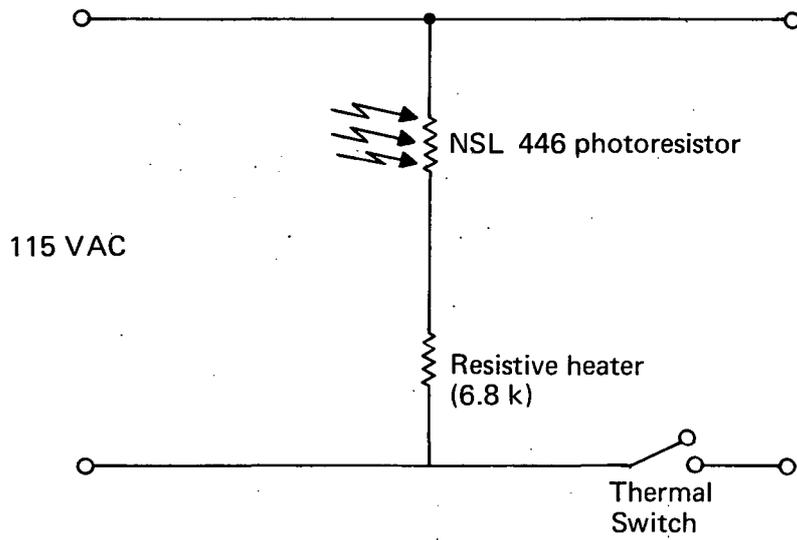
Switch opens when illumination on the photoresistor
increases above 4 ft-cd.

Figure 3
Circuit diagram for "Lumumatic" Day-Night Switch
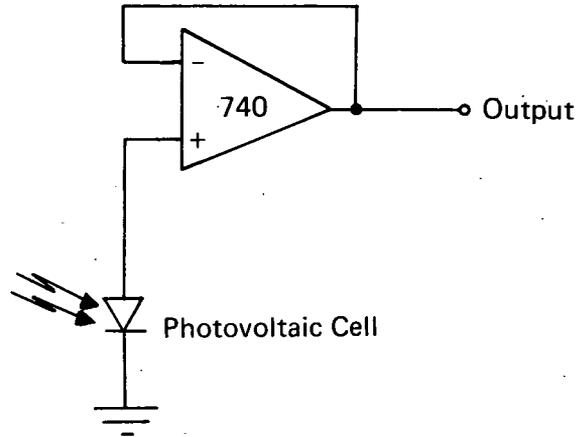
Figure 4

Measuring Circuit for Photovoltaic Cells
using a FET Operational Amplifier 740
as an impedance buffer
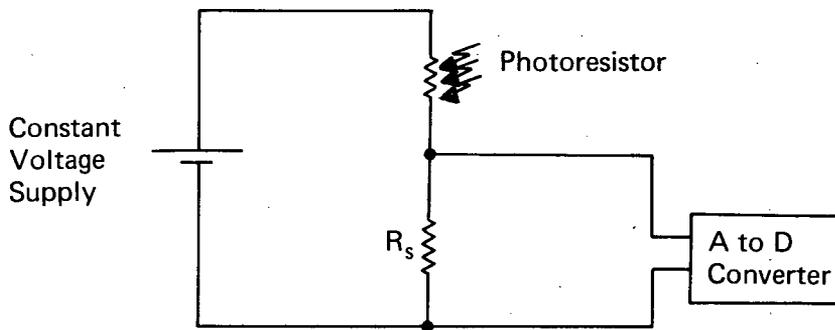
Figure 5
The Photoresistor in an Ohmmeter Measuring Circuit

Photoresistor resistance (ohms)

% of supply voltage

$R_s = 1k$ $R_s = 6.86k$ $R_s = 50k$

"Bright"   "Normal Daylight"   "Intermediate"   "D/N"

Illumination (lux)

Luminance (cd/m^2)
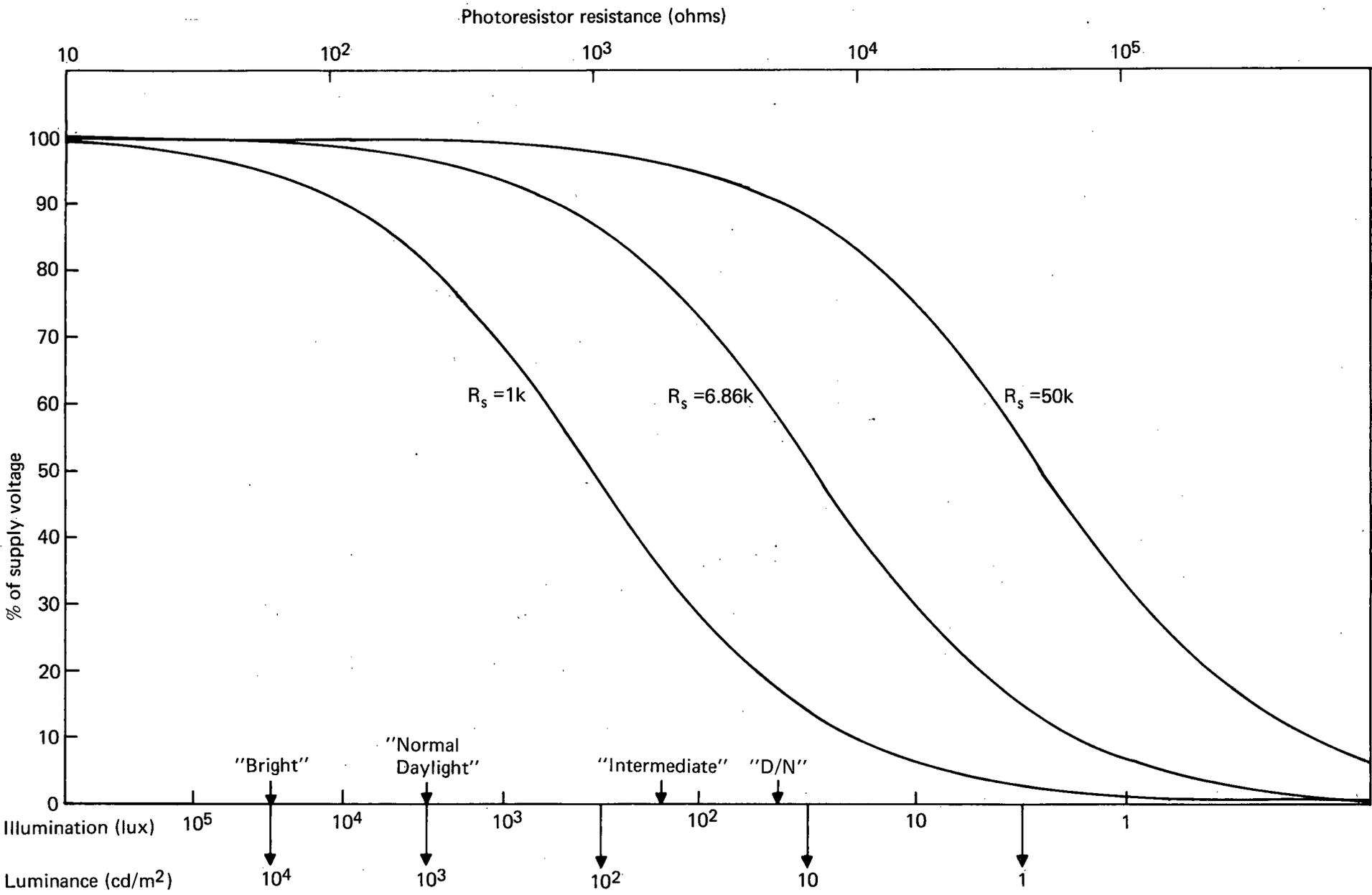
Figure 6

Transfer characteristics for NSL 446 photoresistor as used in the ohmmeter measuring circuit of Figure 4. The percentage of the supply voltage appearing across the series resistor is given as a function of both illumination in lux, and luminance in candles/metre^2 (lower axis), and as a function of the resistance of the sensor, (upper axis), for three values of the series resistor, R_s.

Figure 7
A Photoresistor in a Current Controlled Oscillator Circuit
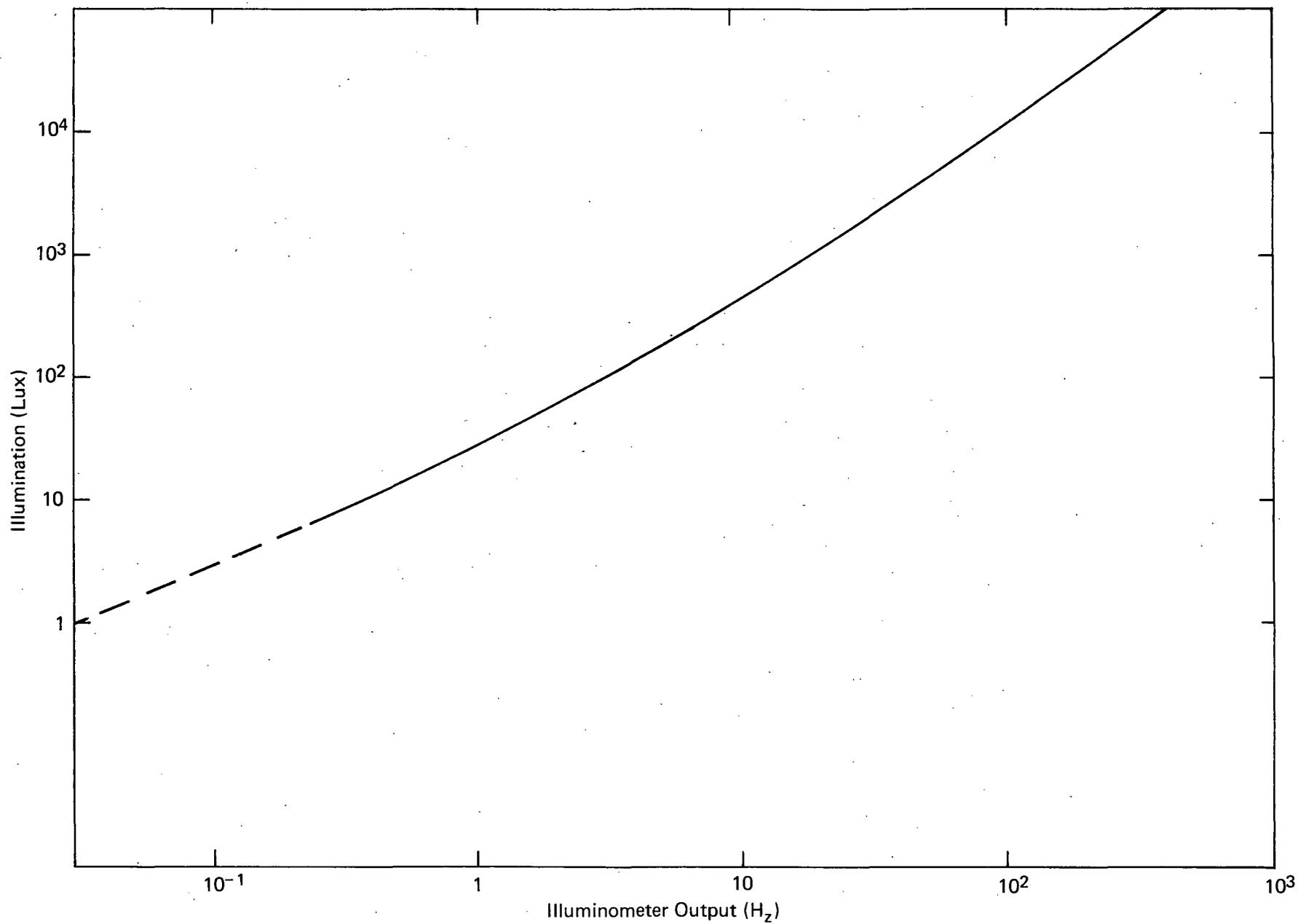
Figure 8
Calibration Curve for the Illuminometer of Figure 7
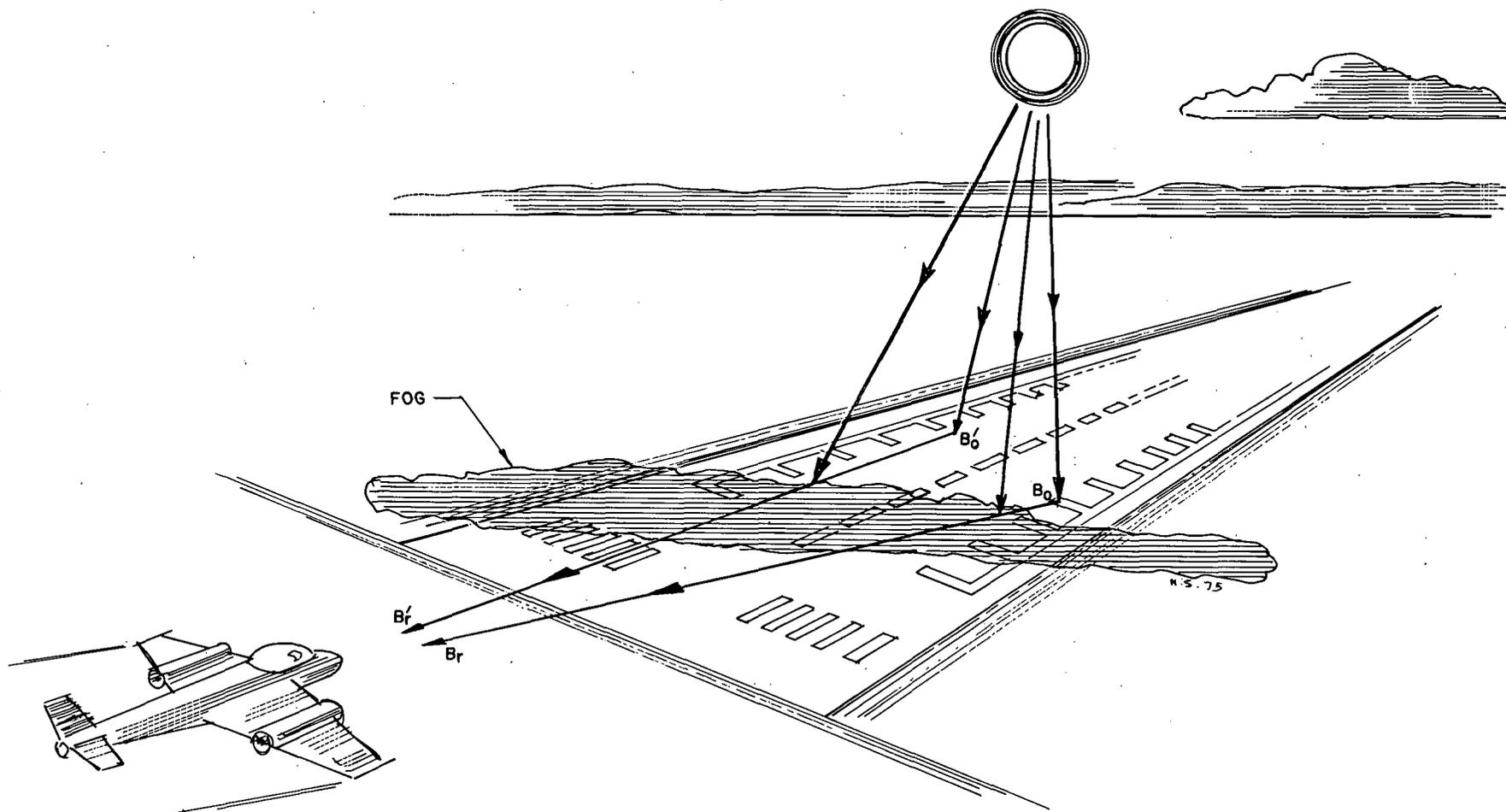
FIGURE 9. An illustration of the effect on RVR of the "veiling luminance" from an illuminated fog over the runway.

The luminance of the runway markings measured at the surface is B_0 and measured at a distance r is B_r.

The luminance of the runway surface measured at the surface is B_0' and measured at a distance r is B_r'.

The luminance of the intervening fog between the runway and the pilot, caused by the atmospheric scattering of light in the direction of observation, effectively augments both B_r and B_r'. This reduces the background luminance ratio, B_0'/B_r', in Equation A.4, resulting in a lower value of the RVR.

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The Development of a Prototype Ambient Light
Sensor for Use in the Runway Visual Range System
by Brian Sheppard

14 pps. 14 refs. 9 figs. 2 tables 4 appen.
Subject Reference: 1. Visibility Measurements
                    2. Toronto, Ontario

ABSTRACT: This technical memorandum describes the development of a prototype ambient light sensor for use in the runway visual range (RVR) system. We review the definition and the computation of RVR. We compare the values of ambient light related RVR parameters used in Canada with those used by other nations. The advantage of a continuous or multi-level ambient light measurement is considered. The results of laboratory and field tests of photovoltaic cells and photoresistors are compared with the basic sensor performance requirements for such continuous or multi-level light measurements. A circuit using a photoresistor as detector was constructed, calibrated and installed for evaluation at Toronto International Airport.