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CONSIDERATIONS ON THE RELATIONSHIP BETWEEN WHITE AND RED CENTERLINE RUNWAY LIGHTS AND RVR

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16. Abstract
The runway visual range (RVR) for a Type L-850 bidirectional centerline runway light has been calculated for the red and white output ports at three different current settings for both day and night illuminance thresholds. The calculations are based on certain parameters measured in our laboratory on a sample light. The resulting RVRs are compared to the standard RVRs based on the High Intensity Runway Light (HIRL). An analysis is also included on the error introduced by ignoring the spectral transmittance of the atmosphere.

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PREFACE

The work described in this report was performed as a part of the Visibility Measuring Techniques program sponsored by the Federal Aviation Administration. The programs principal objective is to provide a system which will supersede a Slant Visual Range/Approach Light Contact Height Measuring System being developed under Interagency Agreement and utilizing presently available off-the-shelf equipment.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Area of Spectroradiometer Aperature
b	Transmissometer Baseline Distance
CRL	Centerline Runway Light
D	Distance from Light Source to Spectroradicmeter
E	Visual Illuminance
E_t	Visual Illuminance Threshold
$H(\lambda)$	Spectral Irradiance
$G(\lambda)$	Spectral Transmittance
HIRL	High Intensity Runway Light
I	Luminous Intensity
ΔI	Change in Luminous Intensity
$J(\lambda)$	Spectral Radiant Intensity
$K(\lambda)$	Luminous Efficacy of Eye, Photopic
R	Distance from Light Source to Detector
RVR	Runway Visual Range
ΔRVR	Change in RVR
t_b	Atmospheric Transmittance over a Baseline of b feet
t_{250}	Atmospheric Transmittance over a Baseline of 250 feet
γ	Atmospheric Extinction Coefficient
$\gamma(\lambda)$	Spectral Atmospheric Extinction Coefficient
λ	Wavelength
ω	Solid Angle

INTRODUCTION

The Transportation Systems Center of the Department of Transportation is presently engaged in a study program for the Federal Aviation Agency titled "Visibility Measuring Techniques".* This report summarizes the results of one of the tasks under the program. The specific task reads as follows:

"Review ICAO requirements relating lights to be used as a basis of runway visual range (RVR) reports, particularly as applied to runways having centerline lights and edge lights conforming to specifications for Precision Approach Runways. Discuss suitability of the statement that there is a defined relationship between edge lights and centerline lights when the centerline lights change from white to red. Does this modify the pilot's interpretation of the reported RVR, and if so to what extent?"

*PPA No. FA215. GWA No. 72-FA.

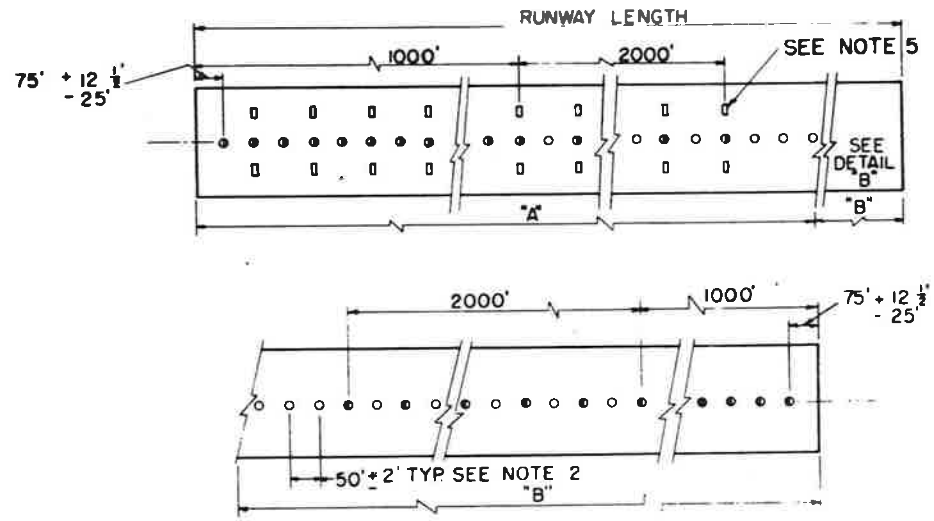
DISCUSSION

An illumination system for Precision Approach Runways using red/white centerline lights is presently being installed at some airports to aid the pilot in determining the runway remaining. Two questions naturally arise: 1) how far away the pilot can detect these lights and 2) is this distance compatible with the present runway visual range (RVR) system?

Figure 1 shows a diagram of the red/white centerline runway lighting system.[1] A system of color coded lights is used to alert the pilot to the runway remaining. Between the last 3000 foot to 1000 foot points on the runway the lights alternate red and white, and for the last 1000 foot portion all the lights are red, thus warning the pilot that he is approaching the end of the runway.

We will calculate the distance that the pilot can just distinguish the centerline runway lights using the same basic laws that form the basis of the present RVR system. We will then examine the spectral effect in the atmospheric extinction coefficient on the visual range.

Figure 2 shows a schematic diagram of the elements relevant to the photometric analysis to determine the relationship between the RVR using runway edgelights and centerline lights (red/white). On the left is a light characterized by a source spectral radiant intensity, $J(\lambda)$, in units of watt steradian^{-1}millimicron^{-1} (w sr^{-1} mμ^{-1}). For the colored light a filter of spectral transmittance $G(\lambda)$ is permanently attached over the lamp. The atmosphere is characterized by an extinction coefficient, $\gamma(\lambda)$. The pilot's visual system is characterized by the illuminance threshold E_t, and the eye's spectral luminous efficacy, $K(\lambda)$. The problems to be solved are, for this given system, 1) to define the relationship between the RVR of the edgelights and centerline lights when the centerline lights change from white to red and 2) to determine whether this modifies the pilot's interpretation of the reported RVR, and if so to what extent?



DETAIL "B"

SYMBOLS

- ▯ — Unidirectional touchdown zone light
- ○ — Bidirectional runway centerline light white both directions
- r ◐ w — / w ◑ r Centerline lights white (w) one direction and red (r) opposite direction

NOTES

1. In rigid or flexible pavement all centerline lights may be offset 2' to the right or left of the runway centerline to avoid the centerline paint markings.
2. The centerline lights may have only a longitudinal tolerance of ± 2'.
3. The last 3000 - foot to 1000 - foot section of the runway centerline displays an alternate red and white light signal.
4. The last 1000 - foot section of the runway centerline displays an all red signal.
5. The touchdown zone light bar are not required to be in line with centerline lights. See figure 2 for configuration.

Figure 1. Runway Centerline Lighting Layout (Advisory Circular AC150/5340-4B, 5/6/69)

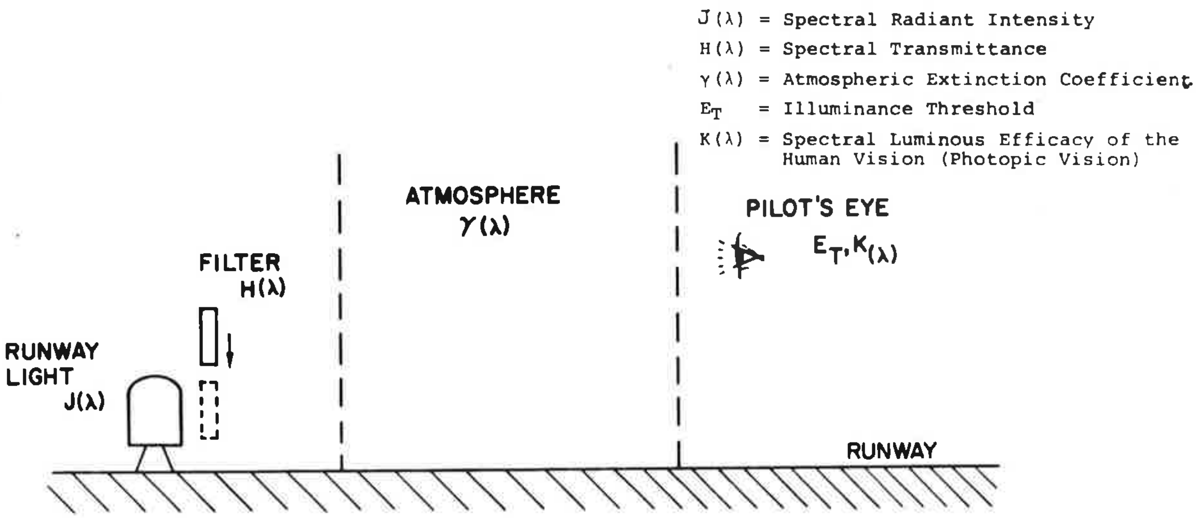


Figure 2. Schematic Diagram Showing the Elements Relevant to the Photometric Analysis to Determine the Relationship Between the RVR Using High Intensity Runway Lights and Centerline Runway Lights (White/Red)

At present in the United States RVR is defined as follows: RVR is an instrumentally derived value, based on standard calibrations, that represents the horizontal distance a pilot will see down the runway from the approach end; it is based on the sighting of either high intensity runway lights or on the visual contrast of other targets, whichever yields greater visual range.[2,3]

The theoretical basis for this definition is Allard's law and the illuminance threshold obtained from measurements on pilots. The general form of Allard's law,

$$E = \frac{Ie^{-\gamma(\lambda)R}}{R^2} \qquad (1)$$

describes the illuminance produced at a distance R from a point source of luminous intensity I through an attenuating atmosphere described by the extinction coefficient $\gamma(\lambda)$. When E is set equal to the illuminance threshold of the pilot's eye, E_t, and I specified, R will be the distance at which the pilot can just distinguish the presence of the luminous source. For the RVR system, E_t is taken as 2 mile candles at night and 1000 mile candles during the day. I corresponds to the high intensity runway lights (HIRL), which at their maximum setting (Step 5) produce a peak of 20,000 candelas. However, 10,000 candelas is used in the RVR computation.

In the present RVR system, Equation (1) can be rewritten in the form,

$$E_t = \frac{I\ t_b^{R/b}}{(R/5280)^2} \qquad (2)$$

where R is the RVR in feet, t_b the average atmospheric transmittance measured by a transmissometer over a baseline of b feet, and E_t is the pilot's illuminance threshold given in mile candles. The relationship between extinction coefficient $\gamma(\lambda)$ and the transmittance t_b is

$$t_b = e^{-\gamma(\lambda)\ b} \qquad (3)$$

The baseline distance b in present FAA transmissometers is 250 or 500 feet. To find the RVR, Equation (2) must be "turned inside out" and solved for R, once the values of E_t, I, are specified and t_b measured. The RVR for the HIRL system has been described previously.[4]

ANALYSIS

In order to derive the RVR for a light consisting of a white light source and a colored filter, we introduce the spectral definition of the luminous intensity,

$$I = \int_0^\infty K(\lambda)\ G(\lambda)\ J(\lambda)\ d\lambda \qquad (4)$$

where $J(\lambda)$ is the spectral radiant intensity of the source and $K(\lambda)$ is the spectral luminous efficacy of the human eye given in lumen $watt^{-1}$. Our visual system defined by $K(\lambda)$ could be for photopic or cone vision, or the scotopic or rod system. For purposes of this analysis the scotopic response, applicable in the dark adapted state, does not arise. The pilot is not dark adapted because of his cockpit illumination[5]. Therefore, in all that following $K(\lambda)$ is for the photopic visual response.

There are two sets of units in use: the photometric and the radiometric ones. The radiometric units are purely physical quantities and almost always contain watts in their units. $J(\lambda)$ which is used above is a radiometric unit. The photometric units automatically take into account the response of the human eye, $K(\lambda)$, through a relationship such as Equation (4). Any unit containing lumens is a photometric unit, such as candelas (lumen $steradian^{-1}$), and foot-candles (lumen $foot^{-2}$). To add to the confusion, sometimes the same symbol is used for the analogous quantity in both systems, e.g., Q for radiant energy (radiometric unit) and luminous energy (photometric unit). Equation (4) can be regarded as a bridge between the radiometric and photometric systems of units.

Let us combine Equations (1) and (4) to get a general form of Allard's law, applicable to any illumination system;

$$E_t = \frac{1}{R^2} \int_0^\infty R^{-\gamma(\lambda)R} K(\lambda)\ G(\lambda)\ J(\lambda)\ d\lambda \qquad (5)$$

The exponential factor must be included under the integral since in the most general case γ is a function of λ. $G(\lambda)$ is the spectral transmittance of the colored filter placed over one port of the bidirectional centerline runway light. When the filter is not present, $G(\lambda)$ is simply unity for all wavelengths. It will later be shown that the wavelength dependency of γ has a small effect on the RVR. Therefore, let us simplify Equation (5) by taking the exponential out from under the integral sign,

$$E_t = \frac{e^{-\gamma R}}{R^2} \int_0^\infty K(\lambda)\ G(\lambda)\ J(\lambda)\ d\lambda \qquad (6)$$

and make the following observation. When two light sources have the same luminous intensity, the RVR for both sources is the same, regardless of the color of the light. This statement follows directly from Equation (6). When two sources have the same luminous intensity, it means that the integral has the same numerical value for each source. This is just a number. Therefore, the same value of R will balance Equation (6), and hence the RVR is the same for both sources. In other words, to the eye, the RVR of a red one candela light is the same as a green (or white, or blue, etc.) one candela light.

Therefore, if we are given the problem of determining the difference in the RVR between two different sources, and we also know that the sources have the same luminous intensity (candelas), and that the atmospheric extinction coefficient does not depend on wavelength, the answer follows immediately; there is no difference in RVR between the sources.

In the case of the bidirectional centerline runway light[6] we can immediately say, by Equation (6) and the way the lamp is constructed, that the RVR for the red port is less than the RVR for the white port. This is because, as shown in Figure 3, a single filament acts as the source for each output port. The optics in each half are the same, except that the red port has an intervening red filter. Its transmittance, $G(\lambda)$, in Equation (6) is numerically less than 1.0 at all wavelengths. Therefore, a smaller value of R is required to balance the equation when the filter is present.

DETERMINATION OF RVR FOR THE RED/WHITE CENTERLINE RUNWAY LIGHT

To calculate the RVR, one must solve Equation (6) for R, after first substituting the appropriate quantities for $K(\lambda)$, $G(\lambda)$*, and $J(\lambda)$, and doing the indicated integration. We are still assuming that the atmospheric extinction coefficient γ is not a very strong function of λ, and hence is outside the integral in Equation (6). $K(\lambda)$ is known. We can determine $G(\lambda)$ by measurements. For $J(\lambda)$, we could assume black body radiation if we knew the color temperature and the surface area of the filament. The color temperature decreases for each decrease in the setting of the lights. To approximate the black body curve, using Wien's Law, would require a fourth order polynomial in λ. The integration then becomes difficult. In addition, one would have to calculate the collection properties of the lenses contained in the lights. Because of all these difficulties, it was decided to abandon the theoretical approach, obtain a #L-850 Light, and measure $J(\lambda)$ and $J(\lambda) \cdot G(\lambda)$ directly with a

*The red used in this filter is the standard "Aviation Red", whose characteristics are set by Military Specification MIL-C-25050(ASG). The standards are set up in terms of the C.I.E. color coordinate system. Unfortunately, there is no way to get from this C.I.E. description to the spectral plot $G(\lambda)$.

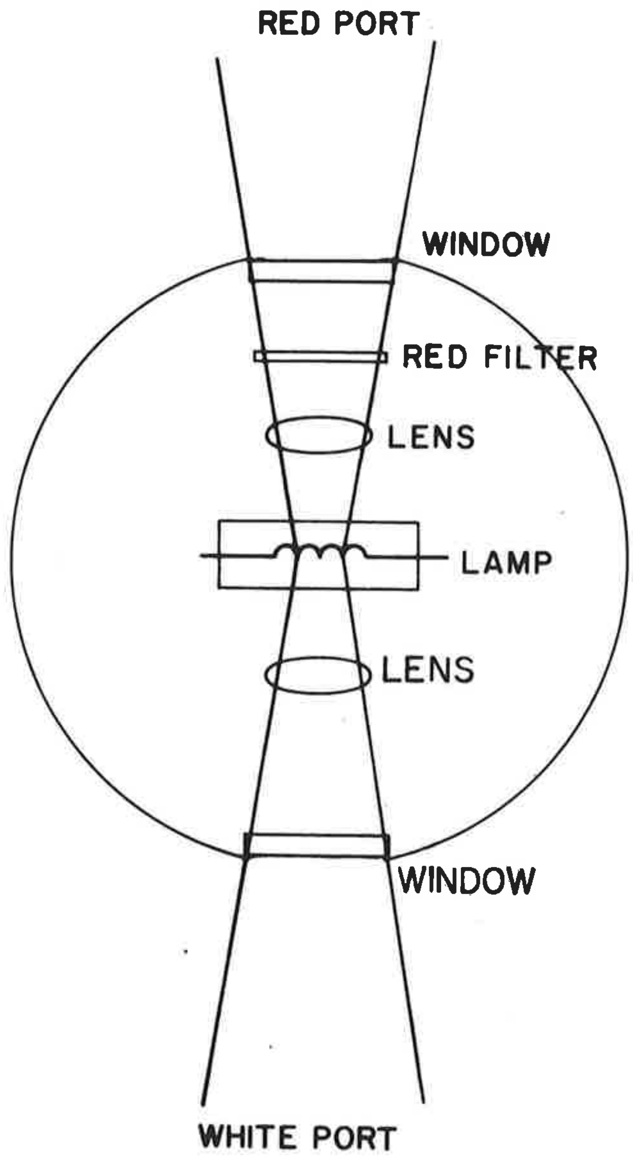


Figure 3. Type L-850 Bidirectional Centerline Runway Light, Top View

spectroradiometer.

The measurements were made every 25 mμ throughout the visible spectrum (400 to 725 mμ). Two measurements were made for each data point, and the average used in the computations. Once J(λ) was obtained, a computer program was written to multiply it by K(λ), the photopic eye luminous efficacy, at each wavelength, and perform the indicated integration numerically to obtain a value for I, the luminous intensity. This entire procedure was done for centerline runway light setting 5, 4, and 3, red and white output ports. Another computer program was written to take this value of I, and the day or night value of E_t, and solve Equation (2) for the RVR.

The set up for measuring J(λ) is shown in Figure 4. The measurement is made using an EG&G model 585 spectroradiometer, which was calibrated by the manufacturer against an NBS-traceable standard. This instrument measures the spectral irradiance, H(λ), in watt cm^{-2} $m\mu^{-1}$. To convert these readings to J(λ), we use the relationship from solid geometry

$$\omega = \frac{A}{D^2} \tag{7}$$

where ω is the solid angle, A the aperture or the spectroradiometer, and D the distance from the spectrometer to the filament.

Therefore,

$$J(\lambda) = H(\lambda)\ D^2 \tag{8}$$

The computer program, which is shown as an appendix and is written in FORTRAN IV for our IBM 7094, takes the output of the spectradiometer, uses the spectral calibration array XK(I) to compute W(λ), converts these numbers to J(λ), multiples by K(λ), array XV(I), and numerically integrates the resultant to give the luminous intensity I in candelas. The absolute accuracy of this procedure is 10% due mainly to the manufacturer's calibration of the spectroradiometer.

The luminous intensity from the white port of our particular light was measured to be 7530 candelas at a setting of 6.6 amps (Step 5). The advisory circular[6] calls for a minimum of 5000 candelas. In order to properly scale down our light, and in

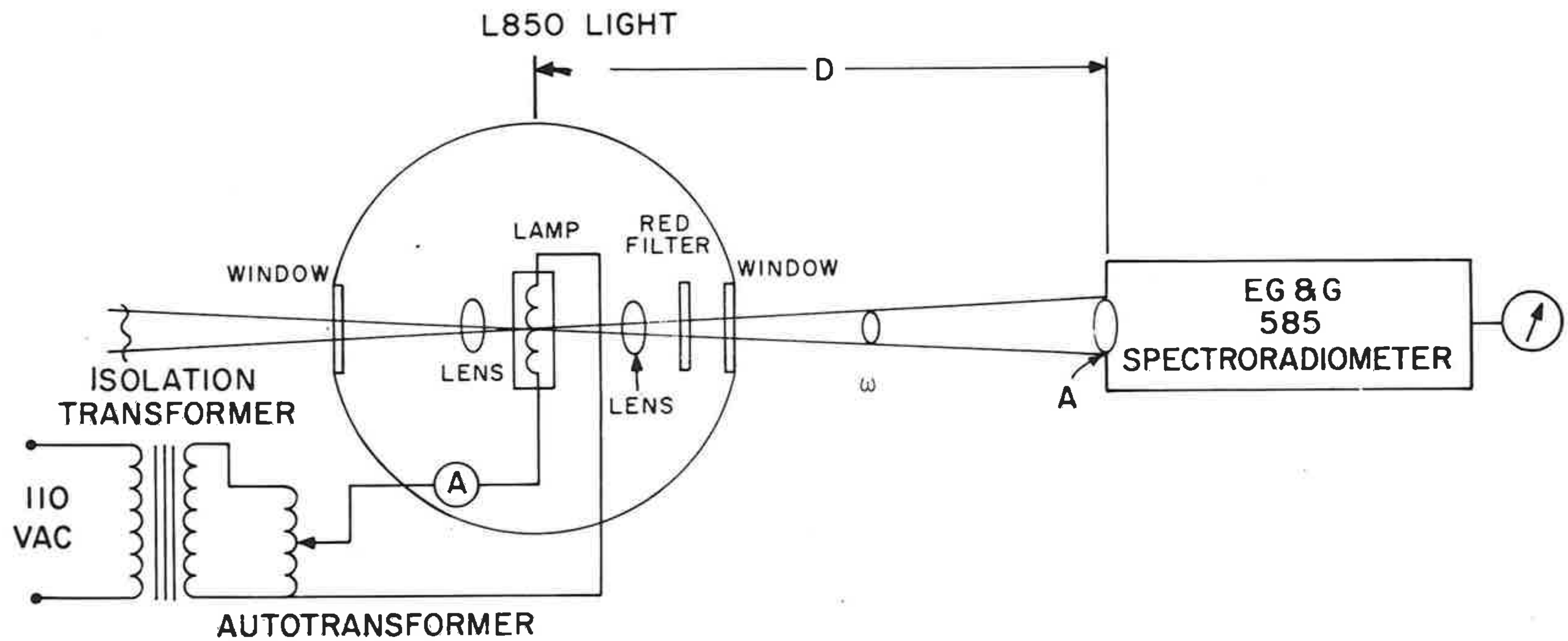


Figure 4. Measurement of the Spectral Radiant Emittance $H(\lambda)$ of an L-850 Centerline Runway Light Using a Spectroradiometer

effect examine the "worst case" RVR, all measured values of luminous intensity were multiplied by 5000/7530 or 0.66401. This has the same effect as placing a neutral density optical filter whose transmittance is 66.4% over the output ports. This procedure does not change the color temperature of the light at the lower settings, and hence does not upset the weighted average of $J(\lambda)$ (Equation 6).*

I was measured in this way for three different lamp current settings; Step 5 (6.6 amps), Step 4 (5.2 amps), and Step 3 (4.1 amps). The results are shown in Table 1. Both the absolute luminous intensity and the intensity normalized to 5000 candelas are shown.

TABLE 1. MEASURED LUMINOUS INTENSITY IN CANDELAS OF CENTERLINE RUNWAY LIGHTS AT THREE CURRENT SETTINGS

	Measured Intensity		Transmittance	Normalized Intensity	
	White	Red	%	White	Red
Step 5	7530	993	13.2	5000	659
Step 4	1600	383	23.9	1062	254
Step 3	278	67	24.1	185	44

Another program was written for a desk top calculator (the Hewlett-Packard 9100) to take these six normalized values of I, the day or night threshold illuminance E_t and solve Equation (2) for the RVR. An estimated value of RVR initiated the program, and the calculator incremented this value by one foot increments until the correct value of E_t was obtained. The results are shown in Figures 5 and 6, and in Tables 2 through 4. Figure 5 shows RVR plotted against t_b, with E_t and I as parameters. The transmissometer baseline distance was assumed to be 250 feet. The CRL RVR is always less than the HIRL RVR, but the percentage by which it is less is not constant. However, Figure 6 does show that the change in RVR is a linear function of reported RVR under all conditions. In Figure 6 the RVR for the HIRL and the centerline runway lights (CRL), both at the same setting, is plotted against the HIRL RVR.

*According to the manufacturer of the L-850, 7500 candelas is representative of the luminous output of this light. One could also scale down the output by correctly choosing a lower color temperature, a much more difficult procedure. Since the advisory circular[6] does not specify a color temperature, or spectral radiant energy curve, we choose the simpler procedure.

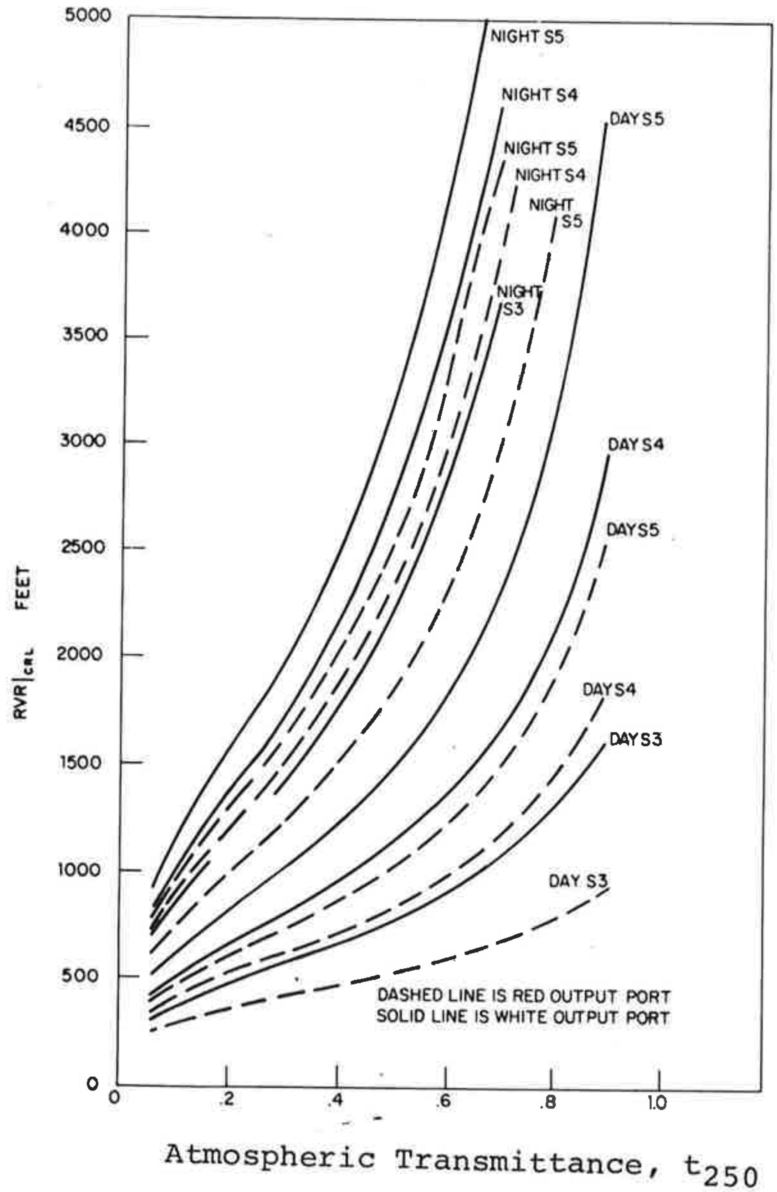


Figure 5. RVR for CRL in Feet Vs. Atmospheric Transmittance for a Transmissometer Baseline of 250 feet.

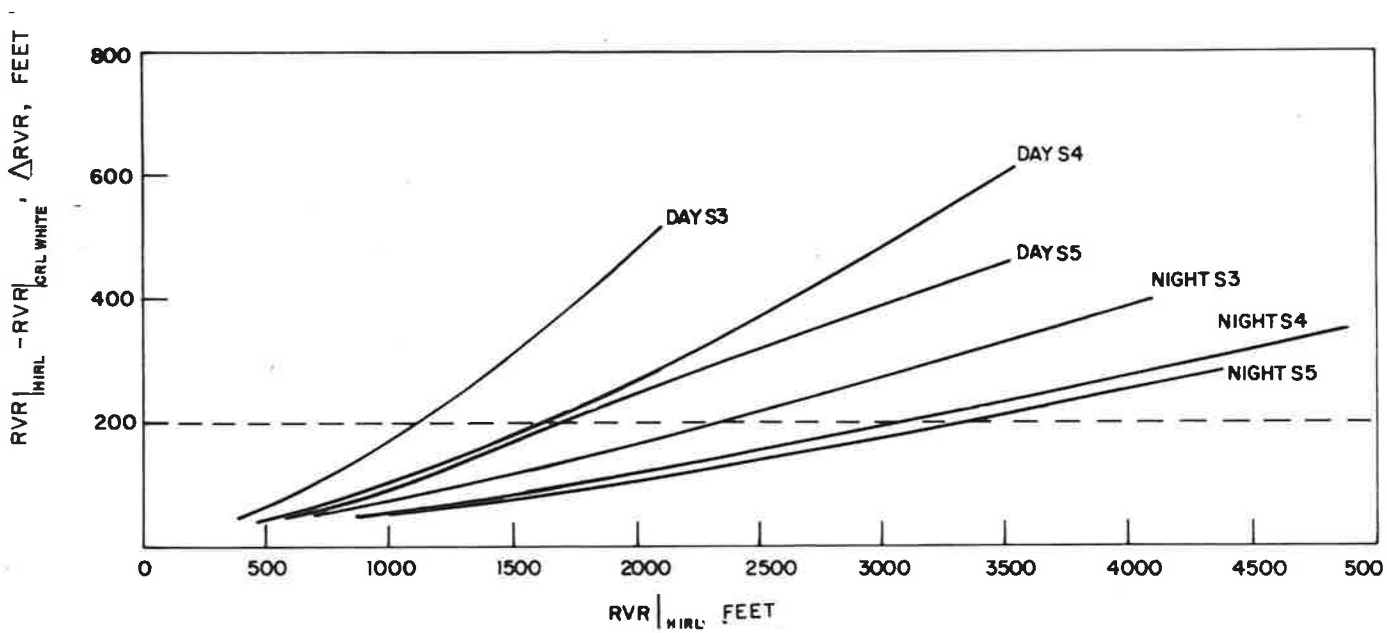


Figure 6. ΔRVR for white light HIRL RVR.

TABLE 2. COMPUTED DAY AND NIGHT RVR (LIGHT SETTING 5) FOR CRL AND HIRL. ALL DISTANCES ARE IN FEET

Atmospheric Transmittance t_{250}	$RVR\|_{CRL}$ White Light 5000 Candelas	$RVR\|_{CRL}$ Red Light 993 Candelas	$RVR\|_{HIRL}$ White Light 10,000 Candelas	$RVR\|_{HIRL} - RVR\|_{CRL, WHITE}$ %	$RVR\|_{HIRL} - RVR\|_{CRL, WHITE}$ Ft.
Day - E_t = 1000 mile-candles					
0.05	521	398	566	8.6	45
0.1	635	477	692	9.0	57
0.2	827	608	906	9.6	79
0.3	1018	734	1122	10.2	104
0.4	1233	871	1367	10.9	134
0.5	1493	1030	1664	11.5	171
0.6	1827	1266	2052	12.3	225
0.7	2296	1486	2605	13.5	309
0.8	3041	1866	3501	15.1	460
0.9	4538	2521	5378	18.5	840
Night - E_t = 2 mile-candles					
0.05	941	800	991	5.3	50
0.1	1176	993	1240	5.4	64
0.2	1589	1330	1679	5.7	90
0.3	2024	1680	2144	5.9	120
0.4	2536	2089	2692	6.2	156
0.5	3187	2602	3392	6.4	205
0.6	4082	3299	4357	6.7	275
0.7	5442	4340	5831	7.2	389
0.8	7872	6154	8481	7.7	609
0.9	13,954	10,497	15,194	8.9	1240

TABLE 3. COMPUTED DAY AND NIGHT RVR (LIGHT SETTING 4) FOR CRL AND HIRL. ALL DISTANCES ARE IN FEET

Atmospheric Transmittance t_{250}	$RVR\|_{CRL}$ White Light 1,600 Candelas	$RVR\|_{CRL}$ Red Light 383 Candelas	$RVR\|_{HIRL}$ White Light 2,000 Candelas	$RVR\|_{HIRL} - RVR\|_{CRL,\ WHITE}$ %	$RVR\|_{HIRL} - RVR\|_{CRL,\ WHITE}$ Ft
Day - E_t = 1000 mile-candles					
0.05	426	343	464	8.9	38
0.1	513	405	562	9.6	49
0.2	657	513	725	10.4	68
0.3	798	612	886	11.0	88
0.4	952	717	1064	11.8	112
0.5	1133	836	1276	12.6	143
0.6	1359	980	1544	13.6	185
0.7	1663	1163	1911	14.9	248
0.8	2117	1416	2475	16.9	358
0.9	2934	1817	3541	20.7	607
Night - E_t = 2 mile-candles					
0.05	833	734	877	5.3	44
0.1	1036	909	1093	5.5	57
0.2	1390	1211	1471	5.8	81
0.3	1760	1523	1867	6.1	107
0.4	2192	1885	2331	6.3	139
0.5	2738	2336	2919	6.6	181
0.6	3450	2944	3723	7.0	243
0.7	4594	3842	4937	7.5	343
0.8	6549	5385	7082	8.1	533
0.9	11286	8979	12356	9.5	1070

TABLE 4. COMPUTED DAY AND NIGHT RVR (LIGHT SETTING 3) FOR CRL AND HIRL. ALL DISTANCES ARE IN FEET.

Atmospheric Transmittance t_{250}	$RVR\|_{CRL}$ White Light 278 Candelas	$RVR\|_{CRL}$ Red Light 665 Candelas	$RVR\|_{HIRL}$ White Light 400 Candelas	$RVR\|_{HIRL} - RVR\|_{CRL, WHITE}$ %	$RVR\|_{HIRL} - RVR\|_{CRL, WHITE}$ Ft.
Day - E_t = 1000 mile-candles					
0.05	325	250	369	13.5	44
0.1	386	291	441	14.3	55
0.2	482	355	557	15.6	75
0.3	573	412	669	16.8	96
0.4	668	470	788	18.0	120
0.5	775	532	926	19.5	151
0.6	903	601	1094	21.2	191
0.7	1063	683	1311	23.3	248
0.8	1281	783	1621	26.5	340
0.9	1615	915	2132	32.0	517
Night - E_t = 2 mile-candles					
0.05	713	617	765	7.3	52
0.1	881	758	949	7.7	68
0.2	1171	999	1267	8.2	96
0.3	1471	1249	1597	8.6	126
0.4	1817	1523	1981	9.0	164
0.5	2249	1867	2462	9.5	213
0.6	2827	2320	3111	10.1	284
0.7	3679	2974	4077	10.8	398
0.8	5133	4058	5747	12.0	614
0.9	8486	6418	9691	14.2	1205

The 200 foot increment is shown by a dashed line. The tables show the RVR numerically, as well as the difference in feet and as a percentage change. From the tables, we see that there is no simple relationship between the HIRL and CRL RVR. The CRL RVR is always less than the HIRL RVR, but the percentage by which it is less is not a constant. However, Figure 6 does show that the change in RVR is, to a good approximation, a linear function of reported RVR under all conditions.

VALIDITY OF LUMINOUS INTENSITY INTEGRAL

The standard and universally used method of computing luminous intensity of a light source, and the method used in this report, is Equation (4).

$$I = \int_0^\infty K(\lambda)\ G(\lambda)\ J(\lambda)d\lambda \tag{9}$$

The function $K(\lambda)$ was established in 1931 by an international committee of the C.I.E. Several researchers have conducted experiments, using human subjects, to test the validity of this approach.[7-10] One of the most thorough investigation was that of Middleton and Gottfried.[7] Their results show that for colored sources blue through orange, Equation (4) is reasonably accurate. However, in the red end of the spectrum significant departures were observed. For a red filter, Corning Glass #2421, the luminous intensity observed by 80 subjects was 2.04 times that predicted by Equation (4), and for a red Wratten #30 filter, 37 subjects observed an apparent intensity of 1.44 times that predicted by Equation (4). This discrepancy is related, among other things, to the angular extent of the light source. The C.I.E. curve is based on sources 2° or larger, whereas Middleton's measurements were on point sources 0.5 minutes of arc. Certainly for runway and taxiway lights, the point source description is the more realistic one.

What effect does this consideration have on RVR? G. T. Schappert's report has a graph which answers this question. His Figure 4 shows RVR plotted against luminous intensity. For convenience it is reproduced here and shown as Figure 7. It shows that the RVR is not a strong function of the luminous intensity. If we use Middleton's results, the red output port of the L-850 light at step 5 produces an effective intensity, not of 993 candelas as shown in Table I, but 993 x(2.04 + 1.44)/2 or 1728 candelas. We have used the average of the two values Middleton shows, since it is not known exactly what the proper value is for Aviation Red. The two different intensities, 993

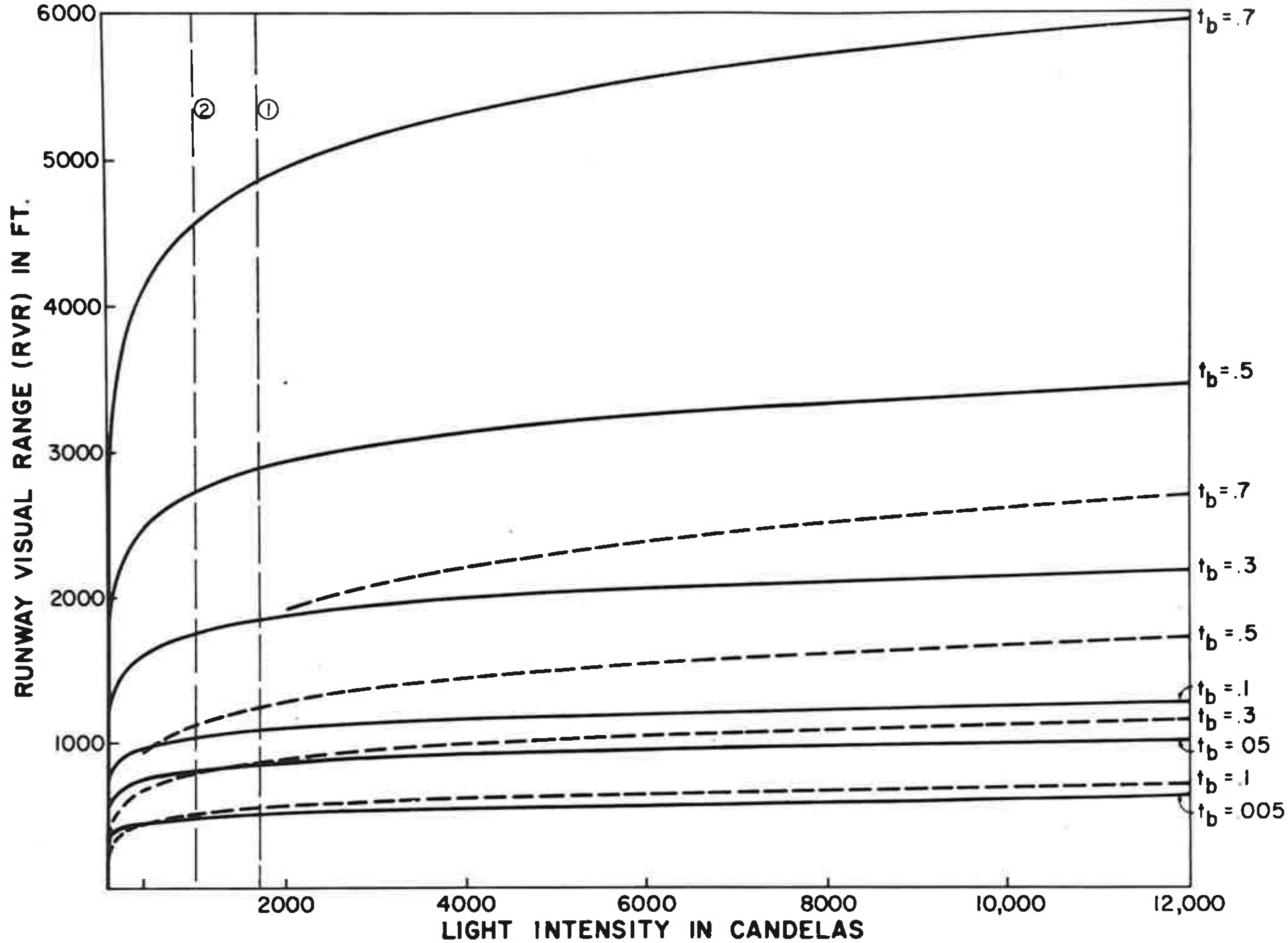


Figure 7. RVR in Feet Vs Luminous Intensity in Candelas as a Function of t_{250} Dashed Curves are for Day and Solid Curves for Night. The Two Vertical Dashed Lines Represent the Intensity of the Red Output Port of the L-850 CRL, 1) with the Middleton Correction, 2) Without the Middleton Correction

1728 candelas are shown as vertical dashed lines in Figure 7. Over this spread of intensities the curves are practically flat - especially for RVRs below 2400 feet (Categories II and III). In addition, the Middleton corrections are fail-safe; ignoring them results in a slightly lower reported RVR.

RVR WHEN EXTINCTION IS A FUNCTION OF WAVELENGTH

All the results to this point have been derived assuming a "colorless" atmosphere, i.e., one which attenuates light of all wavelengths equally. We will now consider what happens to the RVR when the atmospheric extinction coefficient, γ, depends on λ. To do this we must go back to the spectral form of Allard's Law, Equation (5), keeping the attenuation factor $e^{-\gamma(\lambda)}$ under the integral sign;

$$E_t = \frac{1}{R^2} \int_0^\infty e^{-\gamma(\lambda)R} \; K(\lambda) \; G(\lambda) \; J(\lambda) \; d\lambda \qquad (10)$$

As before, the values of E_t, $K(\lambda)$, $H(\lambda)$, and $J(\lambda)$ are known, and the equation must be solved for the transcendental variable R. The function $\gamma(\lambda)$ will be determined from experimental data.[11-13]

We begin by making a series expansion for $\gamma(\lambda)$, retaining only the linear terms.

$$\gamma(\lambda) = \gamma \;\; + k\lambda \qquad (11)$$

Putting (11) into (10) gives

$$E_t = \frac{e^{-\gamma \; R}}{R^2} \int_0^\infty e^{-\lambda k} \; G(\lambda) \; J(\lambda) \; d\lambda \qquad (12)$$

A value of k selected from experimental data[11] is

$$k = -0.45 \text{ km}^{-1} \; \mu^{-1} = 1.37 \times 10^{-7} \text{ ft}^{-1} \text{ m}\mu^{-1} \qquad (13)$$

This value cannot be considered exact, but only representative, since k depends on the size and distribution of the scattering particles. In the study quoted above, k was determined at an average γ corresponding to a t_b of 0.9. Under very foggy conditions the value of k can be as much as four times the value reported by Knestrick.[12] It will be shown the correction depends linearly on the value of k.

The product of $k\lambda$ is 0.25 at midband (.55μ). Therefore, if R is less than 4 km. (13,120 ft.), the exponent is less than 1, and we can expand

$$e^{-k\lambda R} = 1 - k\lambda R \tag{14}$$

Putting this back into (12)

$$E_t = \frac{e^{-\gamma R}}{R^2} \quad [I - \Delta I] \tag{15}$$

where

$$\Delta I = kR \int_0^\infty \lambda \; K(\lambda) \; G(\lambda) \; J(\lambda) \; d\lambda \tag{16}$$

I corresponds to the luminous intensity (normalized) previously calculated and shown in Table 1. To find the RVR for spectral atmospheric extinction, it remains to compute ΔI, put this back into Equation (15) and solve for a new value of RVR. This process can be iterated to converge on the correct value of RVR. However, as the change is small, a reasonably accurate answer can be obtained without iteration. The integral of ΔI was computed using basically the same program as for I, shown in the appendix. The results of these calculations are shown in Table 5. The calculations have been carried out for representative values of RVR, corresponding approximately to 250, 500, 1000, 2000, and 3000 feet. The results are grouped according to the Category I, II, and III (A,B,C) definitions of the visibility limits. t_{250} is the average transmittance corresponding to γ in Equation (11). The HIRL RVR, taken from Tables II, III, and IV and computed for a uniform spectral extinction coefficient, is shown for comparison in column 5. The RVR for the L-850 light is shown in columns 7 and 8 for white and red output ports and includes the effect of a spectral atmospheric transmittance. These RVRs are slightly larger than the corresponding values in Tables 2-4. This is expected since, k being a negative number, means that red light propagates better than blue light. No entries are shown for Category IIIC. This is because the value of t_{250} required to produce a visibility of less than 150 feet, in a transmissometer whose baseline

TABLE 5. SAMPLE RVR FOR HIRL AND CRL, COMPUTED FOR DIFFERENT VISIBILITY CATEGORIES

Visibility Category	Period	Atmospheric Transmittance t_{250}	HIRL, Setting	$RVR\|_{HIRL}$ Feet	CRL, Setting	$RVR\|_{CRL,W}$ Feet	$RVR\|_{CRL,R}$ Feet	$RVR\|_{HIRL} - RVR\|_{CRL,W}$ Feet	$RVR\|_{HIRL} - RVR\|_{CRL,R}$ Feet
I	Night	.5	5	3392	5	3252	2660	130	732
(>2400)	Day	.8	5	3501	5	3179	1942	322	1559
II	Night	.4	4	2331	4	2227	1917	104	414
(1200-2400)	Day	.7	4	1911	4	1688	1166	223	745
IIIA	Night	.1	4	1093	4	1043	915	85	258
(700-1200)	Day	.4	4	1064	4	731	720	333	344
IIIB	Night	.01	3	536	3	508	443	28	93
(150-700)	Day	.01	3	273	3	246	194	27	79
IIIC	Night	$<10^{-8}$							
(0-150)	Day	$<10^{-8}$							

is 250 feet, is less than 10^{-8}, which is certainly beyond the capability of the instrument, for this baseline.

The average change in CRL RVR, for eighteen combinations of t_{250} and day-night illuminance threshold, with and without the uniform γ assumption in 56 feet for the white port and 38 feet for the red one. Hence, we conclude that ignoring the spectral dependency of γ in calculating the RVR is not a serious source of error. It should further be noted that ignoring the spectral dependency of γ errs on the safe side: the actual CRL RVR for both red and white output ports is slightly larger than the same RVR's when the spectral dependency of γ is not taken into account.

CONCLUSIONS

The spectral radiant intensity of the red/white type L-850 bidirectional centerline runway light was measured. From these measurements the luminous intensity and the RVR were calculated. The red port was found to have an output of 13.2% of the white port at current step five, 23.9% at step four, and 24.1% at step three. When the RVR for this light was compared to that of the standard HIRL RVR, it was found that there is no simple relationship between the two quantities. However, the difference in RVR is approximately a linear function of the HIRL RVR under all conditions. The above conclusions were based on the assumption that the atmosphere attenuates light of all visible wavelengths equally.

Experimental data, published elsewhere, indicate that to some extent red light propagated better than blue light. The RVR for the L-850 light was analyzed under this assumption. The RVR was found to increase by 56 feet for the white output port, and 38 feet for the red output port in a sample of 18 cases. Hence, it can be concluded that ignoring the spectral properties of the atmosphere does not introduce a significant error in the RVR computation. Furthermore, the error is on the safe side; the RVR for the spectral atmosphere is slightly larger than the RVR for the spectrally neutral atmosphere.

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APPENDIX

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C       FAA 215 VISIBILITY MEASURING TECHNIQUES
C       DR. J. L. HORNER
C       COMPUTATION OF LUMINOUS INTENSITY IN CANDELAS
C       THIS PROGRAM IS WRITTEN IN FORTRAN IV
C       LIGHT SOURCE L-850 BIDIRECTIONAL CENTERLINE RUNWAY LIGHT WHITE/RED
C       XV(I) IS PHOTOPIC EYE LUMINOUS EFFICIENCY
C       XK(I) IS EGG SPECTRORADIOMETER CALIBRATION
C       XDATA(I) IS SPECTRORADIOMETER OUTPUT CURRENT
        DIMENSION XV(14), XK(14), XDATA(14)
        READ (5,300) (XV(I), I=1,14)
        READ (5,300) (XK(I), I=1,14)
        READ (5,300) (XDATA(I), I=1,14)
   150  FORMAT (31H1LUMINOUS INTENSITY IN CANDELAS)
   151  FORMAT (F20.3)
   300  FORMAT (8F10.3)
C       H IS WAVELENGTH INCREMENT IN MILLIMICRONS
        H = 25.0
C       D IS DISTANCE FROM SOURCE TO SPECTRORADIOMETER IN CM.
        D=396.3
        D2 = D*D
        DO 10 I=1,14
    10  XDATA(I)=XDATA(I)*XV(I)*D2/(XK(I))
        SUM = 0.0
C       INTEGRATION SUBROUTINE
        DO 20 I=1,13
        S = XDATA(I) + XDATA(I+1)
    20  SUM = SUM + S
        XSUM=SUM*H/2.0
        WRITE (6,150)
    30  WRITE (6,151) XSUM
        STOP
        END
```

Computer Program for Calculating Luminous Source Intensity in Candelas from Spectroradiometric Data. Program is Written in FORTRAN IV.