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ATMOSPHERIC PROPERTIES AND REFLECTANCES OF OBJECTS AND BACKGROUNDS FOR A LOW SUN

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FOREWORD

The first and second reports under Assignment 9 of Contract NObs-84075, identified as SIO Ref. 64-3 and SIO Ref. 64-5, contained atmospheric optical data and terrain and background data suitable for use in visibility calculations under the atmospheric and lighting conditions which prevailed at the time of (medium high sun) Visibility Laboratory research flight 74. The third report under Assignment 9, SIO Ref. 65-2, presented the directional luminous reflectance of objects and backgrounds under overcast skies. This, the fourth report prepared under Assignment 9, presents the atmospheric optical properties and directional reflectances of objects and backgrounds for conditions prevailing during (unobscured low sun) Visibility Laboratory research flight 105.

ATMOSPHERIC PROPERTIES AND REFLECTANCES OF OBJECTS AND BACKGROUNDS UNDER A LOW SUN

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ABSTRACT

Measurements of illuminance at sea level, directional luminous reflectance of certain terrains and objects, atmospheric beam transmittance, and path luminance for a day with an unobscured, low sun are presented. These data are applicable for visibility calculations for downward paths of sight.

I. INTRODUCTION

This article is the second of a series of articles in which atmospheric optical properties and directional reflectances of objects and backgrounds are presented in a form which enables the reader to use them for visibility calculations for the downward path of sight. The first article[1] contained data for a clear day with a moderately high sun; it gave a broad coverage of the subject of visibility calculations, including illustrative examples of how to use the data. The data in the present article were obtained under an unobscured sun low in the sky. All of the atmospheric data and some of the reflectance data are from Visibility Laboratory Flight 105.

<u>The flight</u>. Flight 105 was made on 20 April 1957 in the instrumented Air Force B-29 aircraft assigned to the Visibility Laboratory over the Atlantic Ocean east of Patrick Air Force Base, Florida. The recording of data was commenced at 1700 Eastern Standard Time (EST) and was terminated at 1753 EST. At the commencement of data-taking the aircraft was at an altitude of 20 000 ft (6.10 km). Data were recorded at 20 000 ft (6.10 km), during a 1 000-ft (305 m) per minute descent, and at 1 000 ft (305 m). The aircraft then descended to 100 ft (30.5 m) altitude and data were then recorded during an ascent to 1 000 ft (305 m).

Data which were recorded during this flight included sky luminance distributions for the upper and lower hemispherical skies, and the atmospheric attenuation length.

The day was warm, the temperature at take-off being 84° F (26° C). A temperature inversion was noted at about 6 000 ft (1.83 km), the temperature being approximately 61° F (16° C). Scattered clouds were encountered at about 3 000 ft (914 m), and some cirrus clouds were observed to be above 20 000 ft (6.10 km); however, the sun was virtually unobscured.

II. ILLUMINATION

The total downwelling illuminance on a horizontal plane is the result of the sky luminance distribution, the sun luminance, and the zenith angle of the sun. The analysis of the sun and sky luminance distributions for Flight 105 has been limited to the sea level case. Total illuminance on a horizontal plane at sea level was 1710 lum/ft^2 (18 400 lm/m^2) and the ratio of the illuminance from the sky to the total illuminance was 0.490. The solar zenith angle was 77.3°.

The upper sky luminance distribution as measured at sea level for Flight 105 is presented in Fig. 1. The isoluminance map is in polar coordinates. The telephotometer used to measure these luminances had a 5° circular field of view. Accordingly, steep luminance gradients are not resolved and no attempt has been made to depict the rapid change in luminance in the solar aureole. The computed apparent luminance of the sun 1.83×10^8 ft-L (1.97×10^9 apostilbs) was the average for the solar disk and thus represented a value appropriate for a field of view of approximately 1/2°. This sky map defines the distribution of lighting on all non-self-luminous objects at sea level for Flight 105.

The sky luminance distribution, as shown in Fig. 1, was used for the determination of directional reflectances of terrains and objects for use in visibility calculations with the atmospheric data from Flight 105. This will be described in Sections III and IV.

III. DIRECTIONAL REFLECTANCE OF TERRAINS

A directional luminous reflectance, $R_o(0,\theta,\phi)$,* is defined as the ratio of the inherent luminance in the direction of the specified path of sight, $B_o(0,\theta,\phi)$, to the total illuminance on a horizontal plane at sea level, $E_o(0,0,0)$.⁄x

$$R_o(0,\theta,\phi) \equiv B_o(0,\theta,\phi)/E(0,0^\circ,0^\circ) \qquad (1)$$

*The notation for reflectance follows that specified in a paper by Duntley, et al.[2] The subscript zero implies zero observation distance, i.e., inherent reflectance. The three parenthetical symbols, z, θ, and ∅ designate, respectively, the object altitude (which in this case is zero, i.e., sea level), and zenith angle and azimuth of the path of sight.

⁄The notation for illuminance is $E(z,\theta,\phi)$ where z indicates altitude but θ and ∅ specify the position of the normal for the plane upon which the illumination is incident, θ being the zenith angle and ∅ the azimuth. In the case of $E(0,0^\circ,0^\circ)$ the normal is pointing to the zenith, hence the illuminance is that received on a horizontal plane at sea level from the upper 2π solid angle.

xThe luminances in this article are expressed in English and metric units, foot-lamberts (ft-L) and apostilbs, respectively; hence π is not a factor in Eq. (1). If luminances were expressed in English and metric units of candles/ft^2 or candles/m^2, Eq. (1) would be

$$R_o(0,\theta,\phi) \equiv \pi B_o(0,\theta,\phi)/E(0,0^\circ,0^\circ) .$$

In either case, illuminances in lumen/ft^2 and lumen/m^2, English and metric units, respectively, are applicable.

The directional reflectances for various terrains are listed in Tables 1 and 2. These reflectances were determined under lighting conditions typified by an unobscured low sun. Accordingly, these data are suitable for use with atmospheric optical data from Flight 105. Directional reflectances were chosen for tabulation in order to minimize the effect of total illuminance change due to small changes in the zenith angle of the sun. Only with paths of sight where the directional reflectance has a large specular component does a minor change in solar zenith angle cause an appreciable change in reflectance.

The first item in Table 1, the directional reflectance of deep ocean water with a prevailing wind speed of 10 knots, was calculated by means of Eq. (1) from the data recorded during Flight 105. The reflectances for calm ocean water, Item 2, Table 1, and for ocean water during various wind speeds as seen from a vertical path of sight, Table 2, were computed[3] using the luminance distribution of the upper hemisphere from Flight 105 shown in Fig. 1. Note that the measured reflectance of the ocean water during a 10-knot wind for the vertical paths of sight is 0.0230. The average reflectances for the ocean water without white water computed for the same path of sight for wind speeds of 8 and 14 knots were 0.0227 and 0.0228, respectively. Since there should be little or no white water at 10 knots, these computed values are in excellent agreement with the measured value.

Temperature problems and transportation difficulties have precluded the study of real snow surfaces in the natural lighting simulator*

*The natural lighting simulator consists of a 7-foot radius hemisphere with a translucent inner surface and 194 integrating cavities facing that surface. Each integrating cavity has four electric lamps rheostatically controlled for varying the flux level. A projective system of mirrors produces collimated light from a "sun" which can be positioned at any zenith angle and any azimuth in the simulated "sky."

at the Visibility Laboratory. It has been found possible, however, to produce white surfaces which have goniophotometric characteristics duplicating, in all respects, those of snows measured goniophotometrically by Middleton and Mungall.[4] These surfaces are composed of fine glass beads sprayed with very thin coats of white paint. Three types of snow surfaces have been simulated, viz.: snow with surface hoar, snow with rain crust, and snow with a glazed rain crust. The directional luminous reflectances of these simulated snows were measured in the natural lighting simulator. The results are tabulated in Table 1 as Items Nos. 3, 4, and 5. The sky luminance distribution used for these measurements was that of Flight 105 as described in Section II.

The final item, a flat dirt road in the desert, was measured *in situ* under an unobscured low sun.

IV. DIRECTIONAL REFLECTANCES OF OBJECTS

Table 3 presents the directional luminous reflectances under an unobscured low sun lighting condition for two samples of ship's deck paint, and one sample of hull paint measured both wet and dry. The measurement of the second sample of the deck paint and both measurements of the hull paint were made in the natural lighting simulator at the Visibility Laboratory with the sky luminance distribution measured during Flight 105.

V. INHERENT UNIVERSAL CONTRAST

The inherent universal contrast $C_o(z,\theta,\phi)$ is defined as $\rho - 1$ in Ref. (1) when ρ is the ratio of luminance or radiance quantities. The directional reflectances of the object and background, as defined in Eq. (1), are proportional to their luminances and, accordingly, ρ is the ratio of the two reflectances. Thus

$$C_o(0,\theta,\phi) = \frac{{}_tR_o(0,\theta,\phi)}{{}_bR_o(0,\theta,\phi)} - 1 \qquad (2)$$

with the presubscripts t and b indicating that the reflectances are for object and background, respectively.

The designation of "object" and "background" in Tables 1 through 3 is somewhat arbitrary, since what is a background in one case may be the object in another, and vice versa. The data in Tables 1, 2, and 3 can be used in various combinations in obtaining inherent universal contrasts for the late afternoon, low-sun condition.

VI. BEAM TRANSMITTANCE

The measured attenuation length $L(z)$, recorded during Flight 105, is plotted as a function of altitude in Fig. 2. This profile illustrates the usual laminar structure of the atmosphere. Also shown in Fig. 2 is a plot of equivalent attenuation length[8] $\bar{L}(z)$. This quantity, combined with the altitude z, can be used directly in the equation

$$T_r(z,\theta) = \exp\left\{ - \left[z/\bar{L}(z) \right] f(z,\theta) \right\} \tag{3}$$

to obtain atmospheric beam transmittance between sea level and altitude z for a path of sight inclined θ° from the vertical. The factor $f(z,\theta)$ is the relative optical air mass which for zenith angles of from 0° to 70° is, to within 1°/o, equal to sec θ. For zenith angles of from 75° to 88° the values of $f(z,\theta)$ were derived from Kasten's[9] tabulated values of $m(\gamma)$,† the relative optical air mass for the total atmosphere, and his tables of the contribution of the single layers of the atmosphere to the total absolute air mass. Equation (3) with the $f(z,\theta)$ values from Kasten and the $\bar{L}(z)$ values from Table 4 were used for calculating the beam transmittances shown in Figs. 3 and 4.

The uses of the tables and graphs in this paper were illustrated in the first of this series of papers.[10]

† $f(z,\theta) = m(\gamma)$ where $\gamma = 90 - \theta$, and $z = \infty$.

VII. PATH LUMINANCE

Tables 5 through 9 give the path luminances $B_r^*(z,\theta,\phi)$ for paths of sight ranging from directly downward (zenith angle 180°) to 5° below the horizontal (zenith angle 95°) for the azimuths with respect to the sun of 0°, 45°, 90°, 135°, and 180°. The path luminances are for paths of sight from sea level to the observer's altitude. The length of the path is indicated by the subscript r where $r = z \sec \theta$. The increase in the length of the path of sight resulting from the curvature of the earth is greater than 5°/o when $\theta = 95°$ so the path luminances for that zenith angle were not extrapolated above 20 000 ft (6.1 km).

The use of these data for paths of sight between two altitudes is described in Section VI of Ref. (1).

VIII. BACKGROUND LUMINANCE

The inherent background luminances at the time of Flight 105 are presented in polar form in Fig. 5. These luminances are measured quantities but are equivalent to the quantities obtained by multiplying the value of the total illuminance by the reflectance of deep ocean water, Item 1 of Table 1. The telephotometer used to measure these luminances had a 5° circular acceptance angle and, therefore, limited resolution. The luminance gradients near the horizon were not resolved and are omitted from Fig. 5.

The apparent background luminances as measured at 5 000 ft (1.52 km) and 20 000 ft (6.10 km) are presented in Figs. 6 and 7, respectively. These luminances are equivalent to the apparent background luminances calculated by Eq. (4) of Ref. 2:

$$B_r(z,\theta,\phi) = B_o(z_t,\theta,\phi)T_r(z,\theta) + B_r^*(z,\theta,\phi) \quad . \qquad (4)$$

The beam transmittances are those in Figs. 3 and 4; the path luminances are those in Tables 5-9.

These three lower sky luminance distribution maps, Figs. 5-7, serve to illustrate the manner in which the apparent luminance of the sea increases as an observer ascends in altitude. They also provide a means for determining, by interpolation, the apparent luminance of the sea for these altitudes for any angle of sight not in the tables of data presented in the previous sections.

IX. APPARENT UNIVERSAL CONTRAST AND UNIVERSAL CONTRAST TRANSMITTANCE

The apparent universal contrast $C_r(z,\theta,\phi)$ is the product of the inherent universal contrast $C_o(z_t,\theta,\phi)$ and the universal contrast transmittance ${}_b\mathcal{T}_r(z,\theta,\phi)$ where[15]

$$ {}_b\mathcal{T}_r(z,\theta,\phi) = \left[1 + B_r^*(z,\theta,\phi)/T_r(z,\theta)\,{}_bB_o(z_t,\theta,\phi)\right]^{-1} \tag{5}$$

X. REFERENCES

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11. Reference 8.
12. Reference 2, p. 500.
13. Reference 2, p. 501.
14. Reference 2, p. 502.
15. Reference 1, Eq. (6.4)

Table 1 Directional Luminous Reflectance $_{b}R_{o}(0, \Theta, \Phi)$ of Terrains

Description	Sun Zenith Angle	Azimuth Φ of Path of Sight Relative to Sun	Directional Reflectance for Zenith Angle Θ							
			Θ=180	165	150	135	120	105	100	95
1 Ocean water, infinite optical depth, wind speed 10 knots[a]	77.3	0	0.0230	0 0288	0 0390	0 055	0.132	—[b]	0.384	0.358
		45		0.0246	0.0329	0.0417	0.065	0.087	0.104	0.158
		90		0.0242	0.0266	0.0297	0.0373	0.061	0.076	0.093
		135		0.0264	0.0280	0.0309	0.0384	0.072	0.096	0.116
		180		0.0266	0.0288	0.0325	0.0449	0.072	0.099	0.125
2. Calm ocean water, infinite optical depth[c]	77.3	0	0.0224	0.0246	0.0288	0.0471	0.146	—[d]	1.02	1.03
		45		0 0258	0 0269	0 0251	0 0435	0.112	0.193	0.347
		90		0.0211	0.0210	0.0227	0.0435	0.137	0.153	0.245
		135		0 0205	0.0213	0.0231	0.0334	0.0875	0.153	0.347
		180		0.0229	0.0275	0.0488	0 120	0.509	0.823	1.03
3. Snow, with surface hoar[e]	74.0	0	0.69	0.69	0 73[f]	0.78[f]	0 89	1.20	1.39	1.73
		90		0.64	0.65	0.69	0.72	0.73	0.73	
4. Snow, with rain crust (a crust formed by falling rain which does not freeze upon falling)[e]	74.0	0	0 73	0.73	0.74[f]	0 79[f]	0 91	1.47	1.81	2.44
		45		0.71	0.71	0.69	0.67	0.62	0.60	0.58
		90		0.73	0.73	0.71	0.72	0.71	0.69	
		135		0.71	0.74	0.77	0.82	0.89	0.90	
5. Snow, with glazed rain crust (rain crust completely covered by a slightly undulating sheet of ice formed by freezing rainfall followed by warm rain, subsequent freezing temperatures but no further precipitation)[e]	74.0	0	0.80	0.80	0.88[f]	1 13[f]	1.90	5.6	8 4	10.9
		45		0.75	0.77	0.72	0.68	0.65	0.61	0.56
		90		0.75	0.75	0.75	0.74	0.72	0.70	0.65
		135		0.76	0.77	0 80	0.81	0.85	0 84	
6 Dirt, flat desert road, freshly bulldozed to remove encroaching sage[g]	77.8	90	0.230	0.243	0.264	0.275	0 314	0.380	0.426	0.458

[a]Data are from Flight 105.

[b]Value not available, near to direct reflectance from sun.

[c]Computed from equations by Duntley[5] for the lighting condition prevailing for Item 1 in this Table.

[d]Value not computed since sky luminances near sun are poorly defined.

[e]Data taken with a telephotometer April 1960 of simulated snow having reflectance characteristics reported by Middleton and Mungall.[6] The photometry was done in the natural lighting simulator, using the sky luminance distribution from Flight 105.

[f]Data interpolated graphically.

[g]Data taken with a goniophotometer at Naval Ordnance Test Station, China Lake, California, in July and August 1962. The spectral reflectance of a sample of the dirt was measured with a Hardy spectrophotometer. Using C.I.E. Illuminant B, chromaticity coordinates were x = 0.370, y = 0.361, z = 0.269; dominant wavelength = 580mμ and excitation purity = 10%.

Table 2. Uni-directional Luminous Reflectance ${}_{b}R_{o}(0, 180^{o}, 0^{o})$ of Ocean Background: Vertically Downward Path of Sight

Description	Sun Zenith Angle	Zenith Angle θ of Path of Sight	Wind Speed (Knots) 0	2	4	8	14	20	26	32	38
1. Ocean water, infinite optical depth (white water not included in averaging)[a]	77.3	180	0.0224	0.0224	0.0225	0.0227	0.0228	0.0230	0.0231	0.0233	0.0233

[a]Computed from equations by Duntley[7] for the lighting condition prevailing for Item 1, Table 1.

Table 3. Directional Luminous Reflectance ${}_{t}R_{o}(0,\theta,\Phi)$ of Objects

Description	Sun Zenith Angle	Azimuth Φ of Path of Sight Relative to Sun	Normal from Surface: Zenith Angle	Normal from Surface: Azimuth	Directional Reflectance for Zenith Angle θ: θ=180	165	150	135	120	105	100	95
1. Gray Deck Paint[a]	75.7	0	0	0	0.158	0.200	0.307	0.58	1.22	4.80	7.5	11.8
	71.1	90	0	0		0.156	0.151	0.149	0.158	0.190	0.211	0.265
	75.7	180	0	0		0.142	0.146	0.160	0.207	0.352		
2. Glossy Black Deck Paint[b]	74.0	0	0	0	0.0235	0.0350	0.0499	0.118	0.86	530.	2.28	7.0
		45	0	0		0.0312	0.0355	0.0403	0.076	0.228	0.416	0.495
		90	0	0		0.0259	0.0235	0.0302	0.067	0.158	0.221	0.350
		135	0	0		0.0228	0.0269	0.0365	0.058	0.126	0.200	0.55
3. Dull Black Hull Paint, dry[b]	74.0	0	0	0	0.0269	0.0355	0.058	0.171	1.82	60.	50.	30.2
		45	0	0		0.0322	0.0381	0.050	0.082	0.207	0.332	0.47
		90	0	0		0.0283	0.0259	0.0312	0.056	0.144	0.192	0.278
		135	0	0		0.0228	0.0269	0.0351	0.056	0.126	0.186	0.439
4. Dull Black Hull Paint, wet[b]	74.0	0	0	0	0.0173	0.0245	0.0288	0.064	0.120	600.	2.26	1.66
		45	0	0		0.0230	0.0228	0.0307	0.0422	0.197	0.432	0.52
		90	0	0		0.0192	0.0192	0.0221	0.0437	0.127	0.211	0.322
		135	0	0		0.0146	0.0209	0.0273	0.0439	0.102	0.195	0.56

[a]Data were taken with a goniophotometer on 5 February 1953.

[b]Data were taken with a telephotometer. The photometry was done in the natural lighting simulator, using the sky luminance distribution from Flight 105.

Table 4 Measured and Equivalent Attenuation Lengths, and Ratio of Altitude to Equivalent Attenuation Length

Altitude, z		Measured L(z)[a]		Equivalent $\bar{L}(z)$[b]		
(ft)	(km)	(naut mi)	(km)	(naut mi)	(km)	$z/\bar{L}(z)$
0	0	10 3	19 1	10 3	19 1	0
1000	0 305	10 0	18 6	10 3	19 1	0 0159
2000	0 610	8 8	16 3	10 9	20 3	0 0301
3000	0 914	13 2	24 4	11 2	20 7	0 0442
4000	1 22	12 6	23 4	11 6	21 4	0 0570
5000	1 52	24 0	44 4	12 1	22 4	0 0679
6000	1 83	23 2	43 1	13 4	24 7	0 0739
7000	2 13	28 7	53 2	14 4	26 6	0 0802
8000	2 43	28 1	52 1	15 3	28 4	0 0860
9000	2 74	27 9	51 8	16 2	29 9	0 0916
10000	3 05	37 8	70 1	17 1	31 7	0 0961
11000	3 35	28 4	52 5	17 8	33 0	0 102
12000	3 66	28 0	51 9	18 4	34 0	0 108
13000	3 96	28 0	51 9	18 8	34 9	0 114
14000	4 27	30 0	55 2	19 3	35 8	0 119
15000	4 57	33 0	61 2	19 8	36 7	0 125
16000	4 88	33 8	62 6	20 5	37 9	0 129
17000	5 18	38 8	72 0	21 0	38 9	0 133
18000	5 49	45 6	84 6	21 5	39 9	0 138
19000	5 79	39 1	72 4	22 2	41 1	0 141
20000	6 10	40 4	74 9	22 7	42 0	0 145
25000	7 62	47 5	88 0	25 1	46 5	0 164
30000	9 14	56 0	104	27 4	50 8	0 180
35000	10 7	66 2	123	29 8	55 2	0 193
40000	12 2	80 5	149	32 2	59 6	0 205
45000	13 7	102	189	34 6	64 2	0 214
50000	15 2	129	239	37 2	69 0	0 221
55000	16 8	161	299	39 9	73 9	0 227
60000	18 3	206	381	42 7	79 1	0 231
100000	30 5	781	1450	66 0	122	0 249
200000	61 0	2190	4060	128	239	0 254
∞	∞	∞	∞	-	-	0 255[c]

[a] Attenuation length $\bar{L}(z)$ was recorded continuously as a function of altitude from 20 000 feet (6 10 km) to 1000 feet (0 305 km) during descent of airplane at 1000 feet (305 m per min) The 100 ft to 1000 ft data was taken directly afterward during an ascent where the airplane was again held in a level attitude These data are shown in Fig 2 Attenuation lengths from 20 000 feet to 60, 000 feet (6 10 km to 18 3 km) are computed using density ratios derived from Radiosonde data on temperature and pressure Extrapolation from 60, 000 feet to ∞ was made assuming an optical standard atmosphere

[b] The quantity $1/\bar{L}(z)$ is equal to Elterman's mean attenuation coefficient $K_a(h)$, and the two quantities $z/\bar{L}(z)$ and $K_a(h)$ h_1 may be used interchangeably See Elterman[11]

[c] The value of $z/\bar{L}(z)$ where z = ∞ was calculated fromthe sea level to space transmittance obtained from measured and extrapolated attenuation length data

Table 5. Path Luminance $B_r^*(z, \theta, 0^\circ)$[a], Lower Sky in Azimuth of Sun[b]

Altitude[c] (ft)	Path Luminance (ft-L)[d] for zenith angle θ[e,f]							
	θ = 180°	165°	150°	135°	120°	105°	100°	95°
1000	2.42	2.28	4.72	13.1	41.1		92.8	142
2000	5.67	5.61	9.78	29.9	91.2		188	269
3000	9.21	9.42	16.3	48.7	145		288	390
4000	12.9	13.8	23.3	68.2	201		389	500
5000	16.7	19.4	31.1	89.6	267		489	608
6000	21.9	24.1	38.5	113	337		579	702
7000	27.0	30.0	46.9	139	412		684	805
8000	32.7	37.7	56.3	167	494		798	911
9000	37.9	45.5	67.7	194	581		920	1050
10000	44.1	54.2	80.0	224	673		1060	1180
15000	74.1	94.5	144	349	1050		1840	1900
20000	88.8	137	213	483	1430		2710	2780
25000	102	176	276	605	1770		3460	
30000	113	209	329	706	2050		4030	
40000	130	258	408	858	2470		4830	
50000	141	290	460	956	2730		5290	
60000	148	310	491	1020	2890		5560	

[a] Parenthetical symbols: photometer altitude z, zenith angle θ, and azimuth applicable to table.

[b] Zenith angle of sun during flight 77.3°.

[c] In using these tables, it has been found that above 10,000 ft altitude increments of 5000 ft and 10,000 ft are satisfactory.

[d] The tabulated value in ft-L multiplied by 10.76 gives the value in apostilbs.

[e] Path luminances from 0 - 20,000 ft altitudes for zenith angles from 95° to 180° were calculated by means of Eq. 1, Duntley et al.[12]

[f] Path luminances for altitudes above 20,000 ft were extrapolated as follows: (1) Path functions for 20 000 ft B_*(~~2000~~ 20 000, θ, Φ) were calculated from flight data and Eq. 10 of Duntley et al.[12] (2) Path functions above 20,000 ft were calculated in 100-ft increments, in proportion to atmospheric density computed from Radiosonde data (3) Path luminances above 20,000 ft $B_r^*(z, \theta, \Phi)$ were calculated by means of Eq. 17 of Duntley et al.[14]

Table 6. Path Luminance $B_r^*(z, \theta, \pm 45^\circ)$[a], Lower Sky, 45° from Azimuth of Sun[b]

Altitude[c] (ft)	Path Luminance (ft-L)[d] for zenith angle θ[e,f]						
	θ = 165°	150°	135°	120°	105°	100°	95°
1000	2.49	3.13	5.09	7.47	19.9	27.7	71.4
2000	5.09	7.02	9.47	14.5	41.4	57.1	124
3000	8.69	10.9	14.8	23.4	63.5	87.2	173
4000	12.5	15.2	20.0	31.9	87.6	118	218
5000	16.7	19.8	25.5	41.1	113	149	260
6000	21.4	24.2	32.6	49.3	137	178	296
7000	26.6	28.6	39.2	57.4	165	212	336
8000	31.9	34.4	48.7	68.5	195	251	377
9000	38.1	40.3	58.2	80.6	230	291	425
10000	44.8	46.5	67.6	97.4	266	337	480
15000	81.9	83.2	113	191	487	643	895
20000	104	122	152	267	754	1020	1450
25000	124	158	187	335	991	1350	
30000	140	187	216	391	1180	1600	
40000	166	232	260	474	1450	1960	
50000	182	261	288	527	1610	2160	
60000	192	279	306	559	1710	2280	

a, b, c, d, e, f See footnotes to Table 5.

Table 7. Path Luminance $B_r^*(z, \theta, \pm 90^\circ)$[a], Lower Sky, 90° from Azimuth of Sun[b]

Altitude[c] (ft)	Path Luminance (ft-L)[d] for zenith angle θ[e,f]						
	θ = 165°	150°	135°	120°	105°	100°	95°
1000	3.18	3.43	4.14	5.50	13.3	20.4	34.7
2000	6.67	7.15	8.12	11.2	26.5	38.4	65.7
3000	10.4	11.2	12.6	17.9	41.5	57.2	96.6
4000	14.3	15.1	17.9	24.4	56.7	75.3	125
5000	18.5	19.8	23.2	31.6	72.2	94.1	152
6000	23.1	24.1	28.6	38.8	89.1	112	175
7000	28.3	29.4	34.5	46.5	105	129	201
8000	33.5	34.7	41.3	55.1	123	151	229
9000	39.7	41.5	49.2	65.7	140	173	259
10000	46.4	48.2	58.5	76.2	158	199	292
15000	80.5	82.5	95.2	138	297	402	537
20000	99.3	114	129	210	440	674	910
25000	116	143	160	275	567	911	
30000	131	167	186	328	667	1090	
40000	152	204	225	408	811	1340	
50000	166	228	249	458	898	1490	
60000	175	242	265	489	950	1570	

a, b, c, d, e, f See footnotes to Table 5.

Table 8. Path Luminance $B_r^*(z, \theta, \pm 135^\circ)$[a], Lower Sky, 135° from Azimuth of Sun[b]

Altitude[c] (ft)	Path Luminance (ft-L)[d] for zenith angle θ[e,f]						
	θ = 165°	150°	135°	120°	105°	100°	95°
1000	3.44	4.87	5.18	6.16	18.4	29.5	47.2
2000	7.09	8.54	11.0	12.9	36.6	55.9	92.0
3000	11.0	13.3	16.7	21.7	55.5	87.1	135
4000	15.3	18.1	23.1	30.2	74.4	116	177
5000	20.0	23.1	29.8	40.5	94.6	148	219
6000	24.4	28.6	37.3	49.2	117	177	260
7000	30.3	35.2	44.7	59.8	139	211	304
8000	35.4	41.5	53.1	73.5	166	247	353
9000	42.8	49.8	62.4	88.1	196	288	408
10000	50.0	57.0	73.7	105	229	335	469
15000	80.2	96.4	118	184	423	584	847
20000	106	134	153	266	669	828	1300
25000	130	169	184	340	887	1040	
30000	149	197	210	401	1060	1200	
40000	179	241	249	491	1310	1430	
50000	198	269	273	548	1460	1560	
60000	210	286	289	583	1550	1630	

a, b, c, d, e, f See footnotes to Table 5.

Table 9. Path Luminance $B_r^*(z, \theta, 180^o)$[a], Lower Sky, 180° from Azimuth of Sun[b]

Altitude[c] (ft)	Path Luminance (ft-L)[d] for Zenith Angle θ[e, f]						
	θ = 165°	150°	135°	120°	105°	100°	95°
1000	3.15	3.50	4.54	8.41	20.3	36.9	52.7
2000	6.79	7.28	9.12	17.0	40.5	74.7	104
3000	10.4	11.5	14.2	25.5	63.3	115	157
4000	14.0	15.6	19.6	33.3	87.3	158	212
5000	18.0	20.3	25.4	43.8	113	208	269
6000	22.3	25.1	31.3	54.6	139	257	329
7000	27.5	31.0	38.3	66.4	171	311	402
8000	32.3	38.3	46.7	81.2	207	371	486
9000	38.5	46.1	56.1	95.9	247	436	585
10000	44.7	55.3	70.4	116	291	502	689
15000	78.9	103	150	268	564	837	1140
20000	103	148	229	442	910	1230	1680
25000	134	189	300	600	1220	1560	
30000	160	223	360	728	1460	1820	
40000	199	275	449	921	1810	2180	
50000	224	308	506	1040	2020	2390	
60000	239	328	541	1120	2150	2510	

a, b, c, d, e, f See footnotes to Table 5.

Fig. 1 Upper sky luminances measured at sea level, values in foot-lamberts (ft-L). When expressed in apostilbs, the metric luminance unit, the numerical values are increased by the factor 10.76.

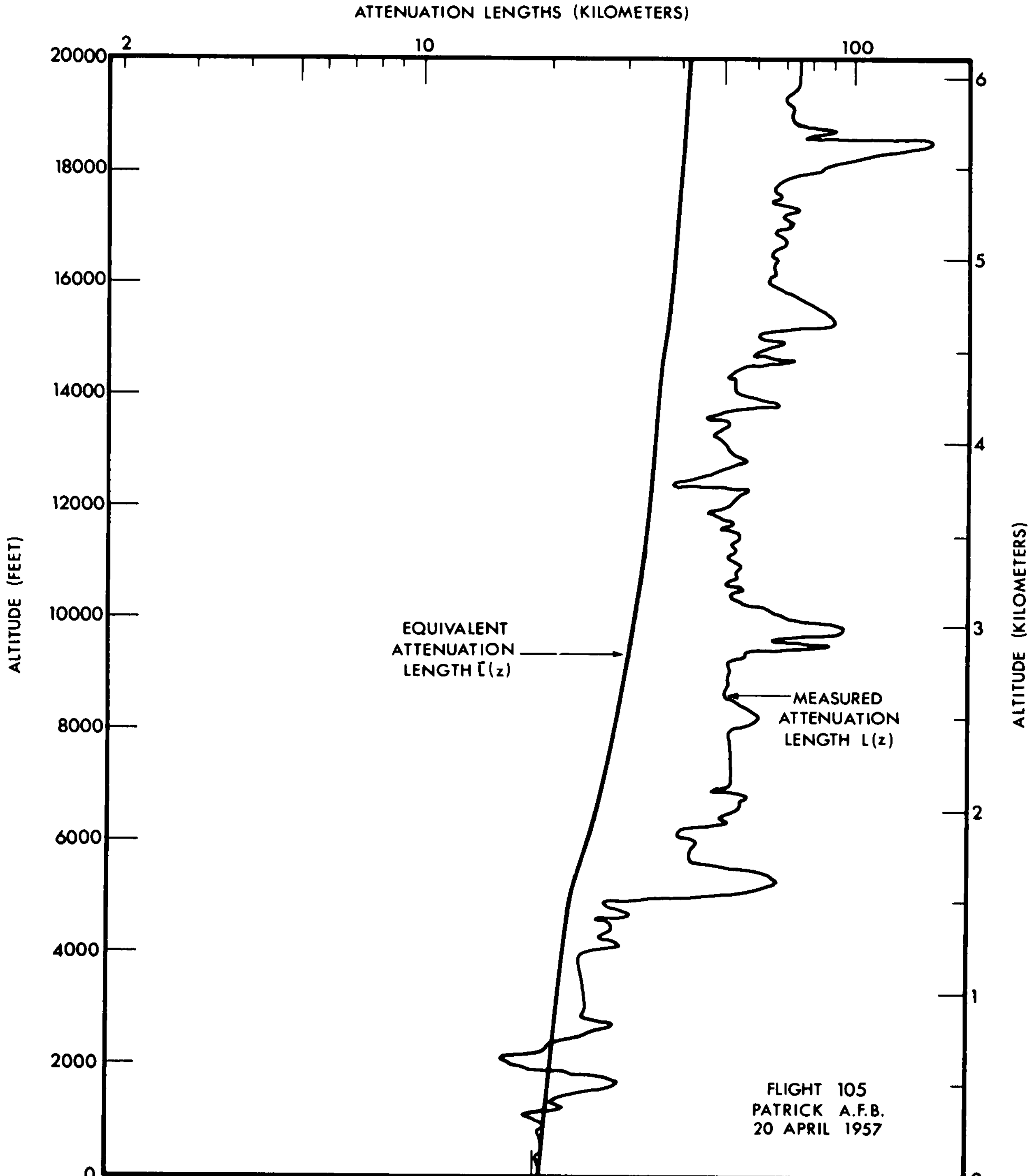

Fig. 2 Attenuation length L(z) measured continuously during 1,000 ft-per-min descent with aircraft held in level attitude. Equivalent attenuation length $\bar{L}(z)$ is computed.

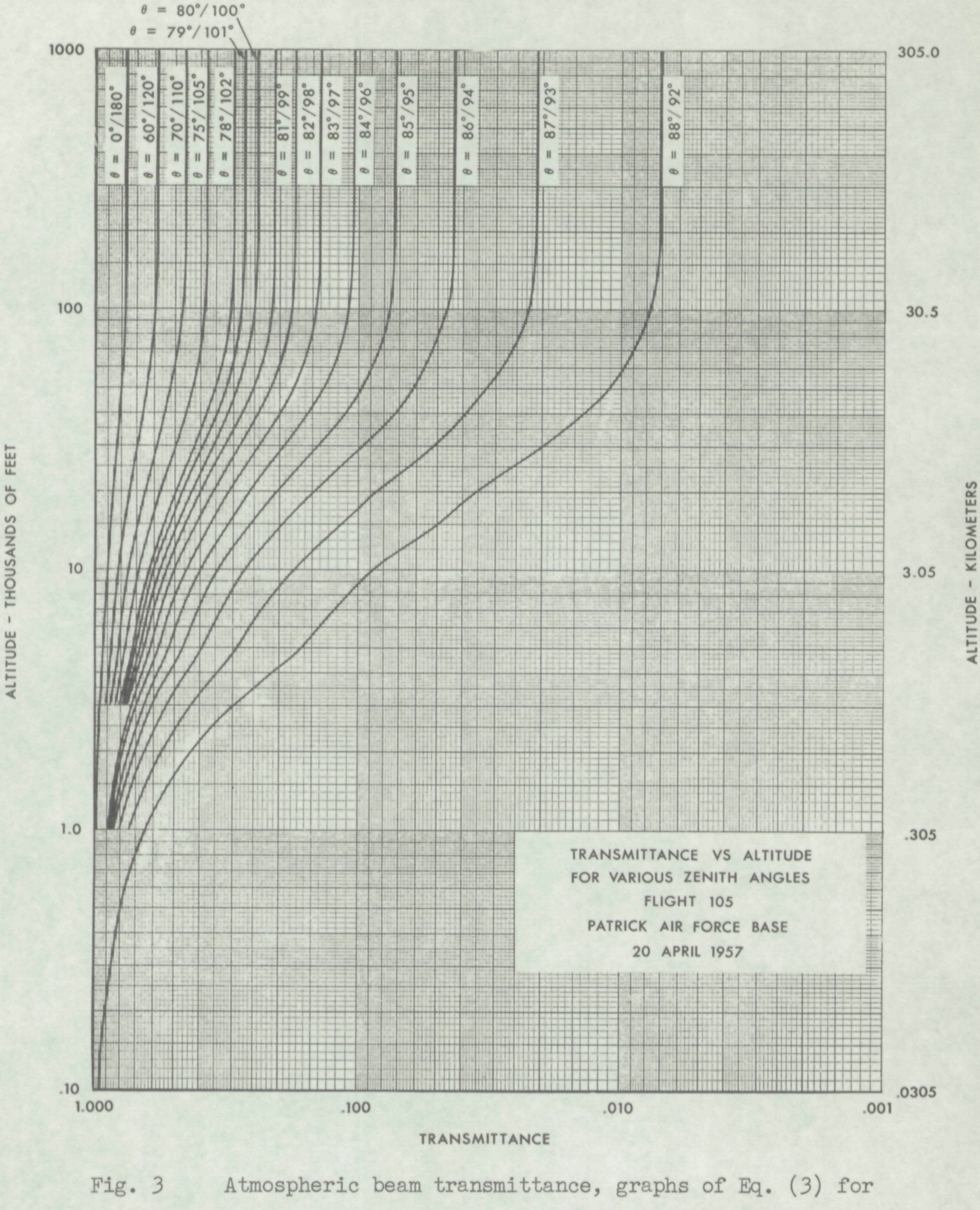

Fig. 3 Atmospheric beam transmittance, graphs of Eq. (3) for various zenith angles from $0/180^{\circ}$ to $88^{\circ}/92^{\circ}$ as indicated.

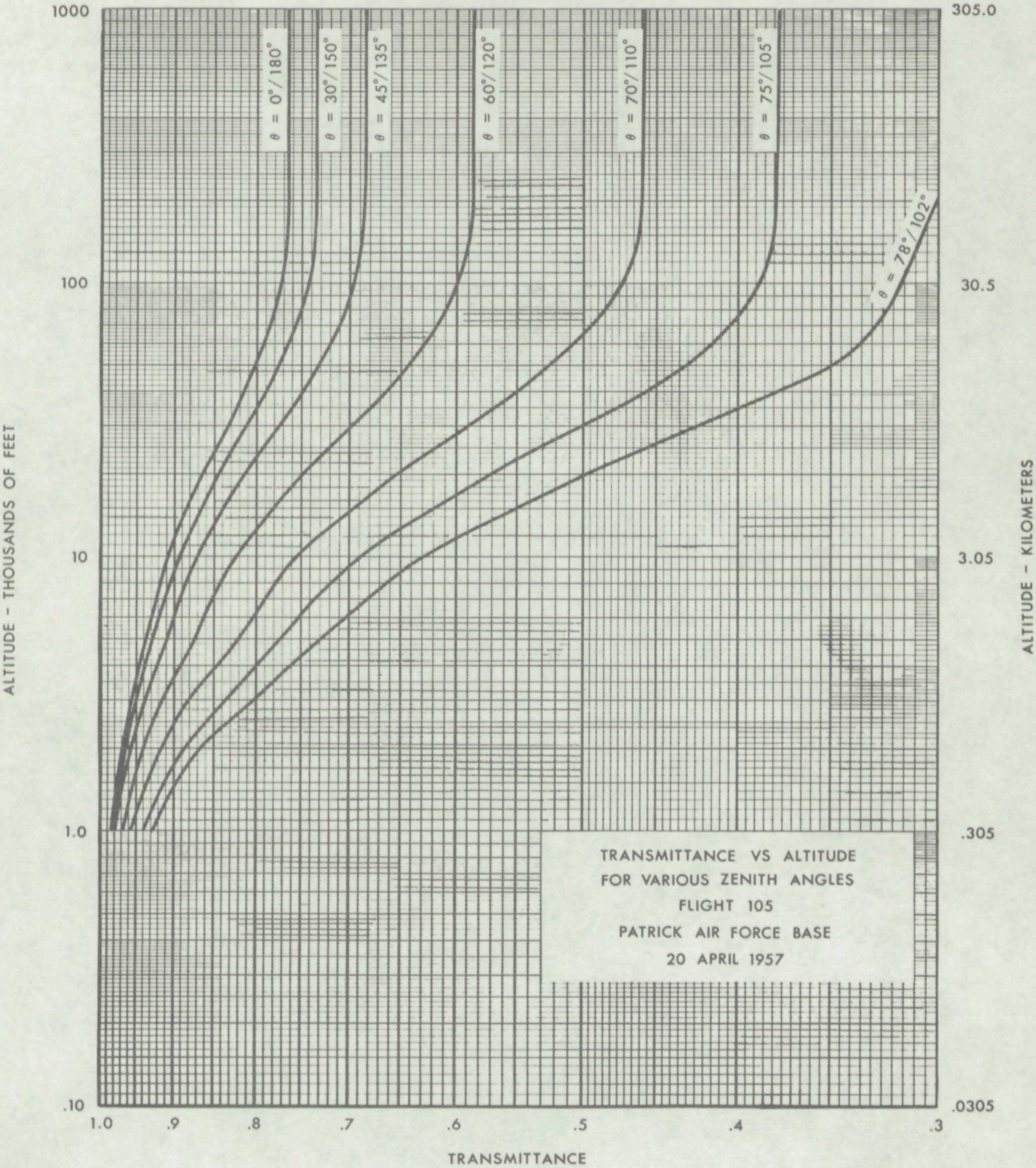

Fig. 4 Transmittances for various zenith angles from $0^{\circ}/180^{\circ}$ to $78^{\circ}/102^{\circ}$ on expanded horizontal scale.

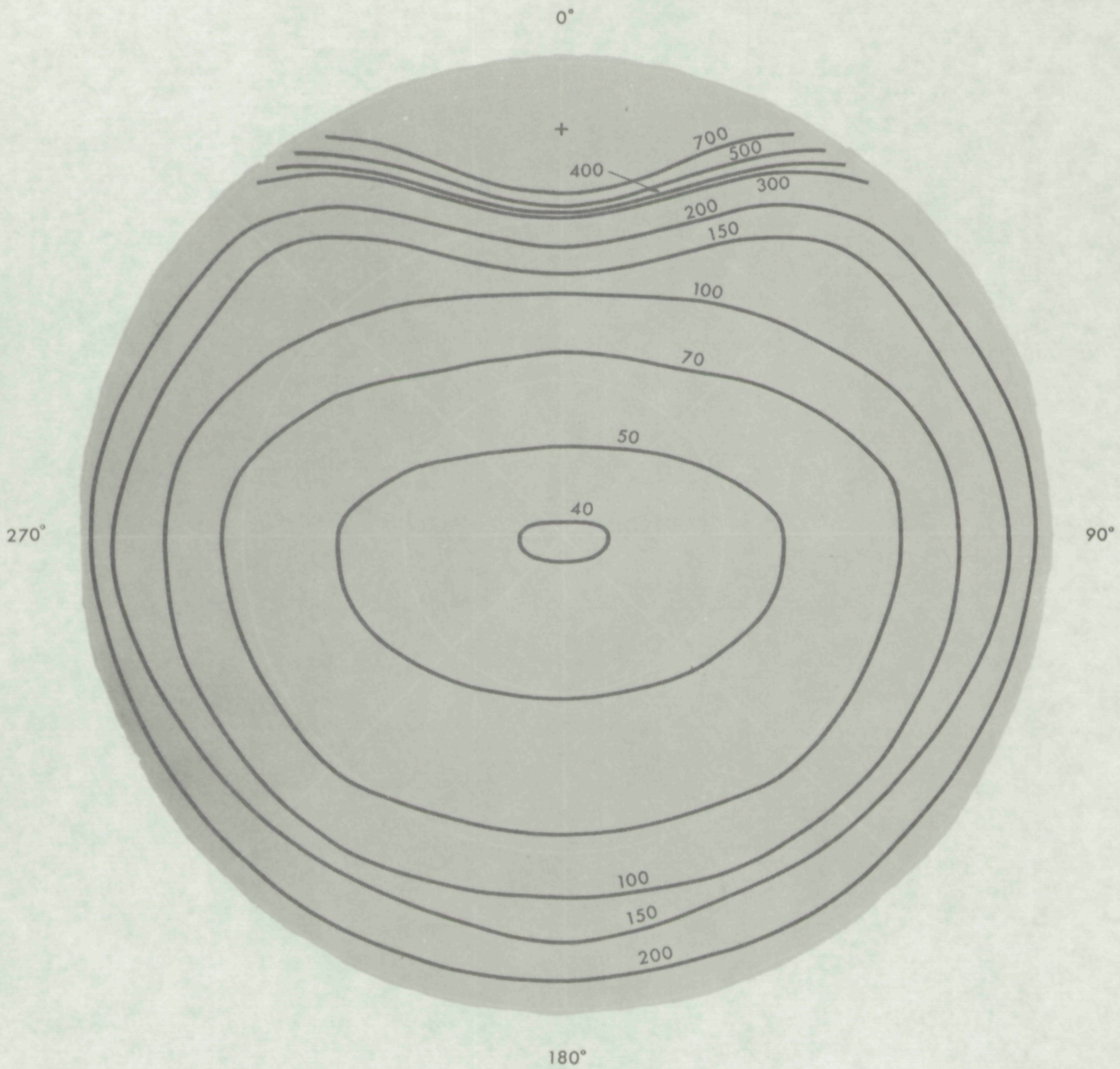

Fig. 5 Lower sky luminance in ft-L. Map depicts the inherent sea luminance at sea level.

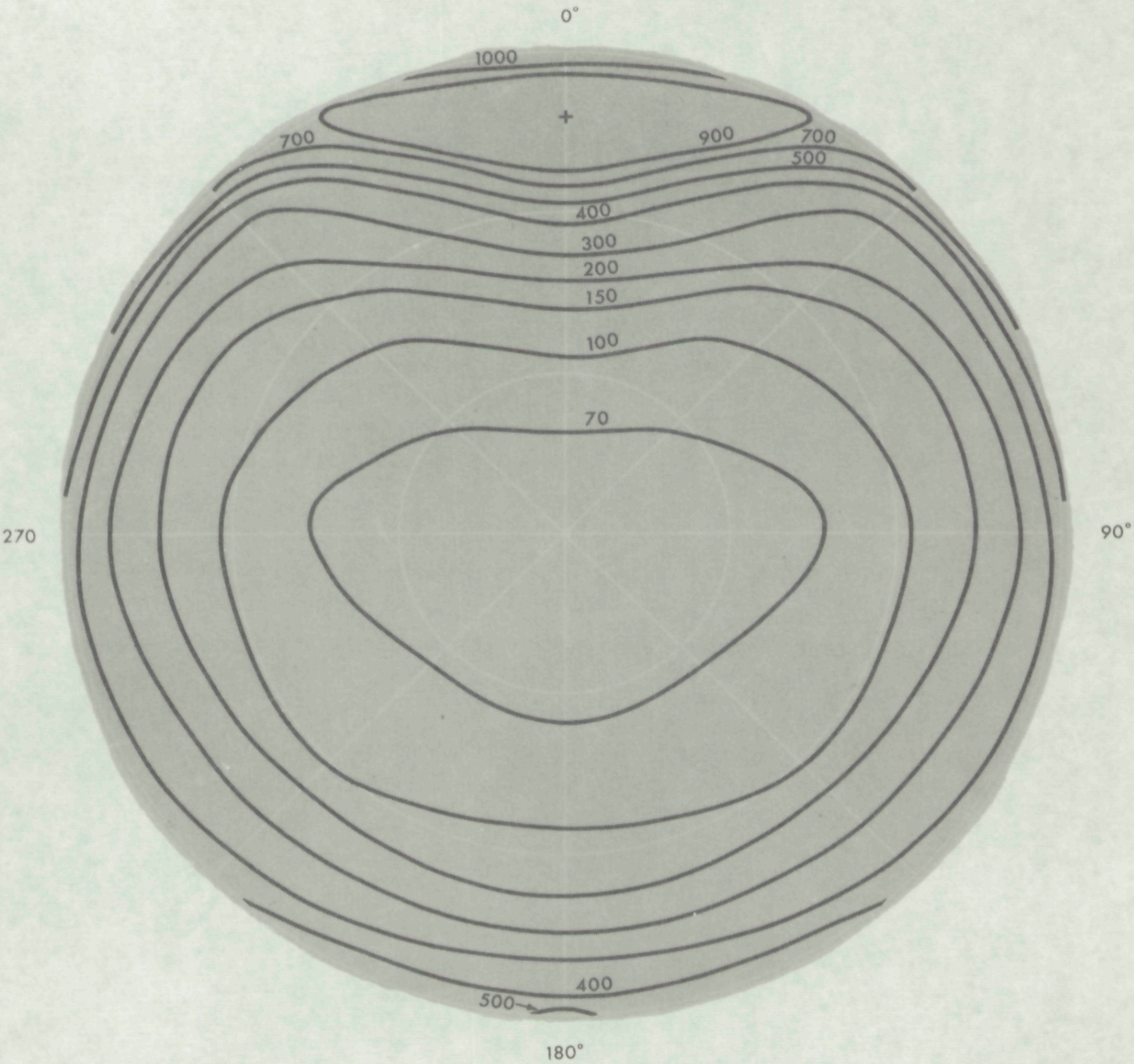

Fig. 6 Lower sky luminance in ft-L. Map depicts the apparent sea luminance at 5,000 feet (1.52 km).

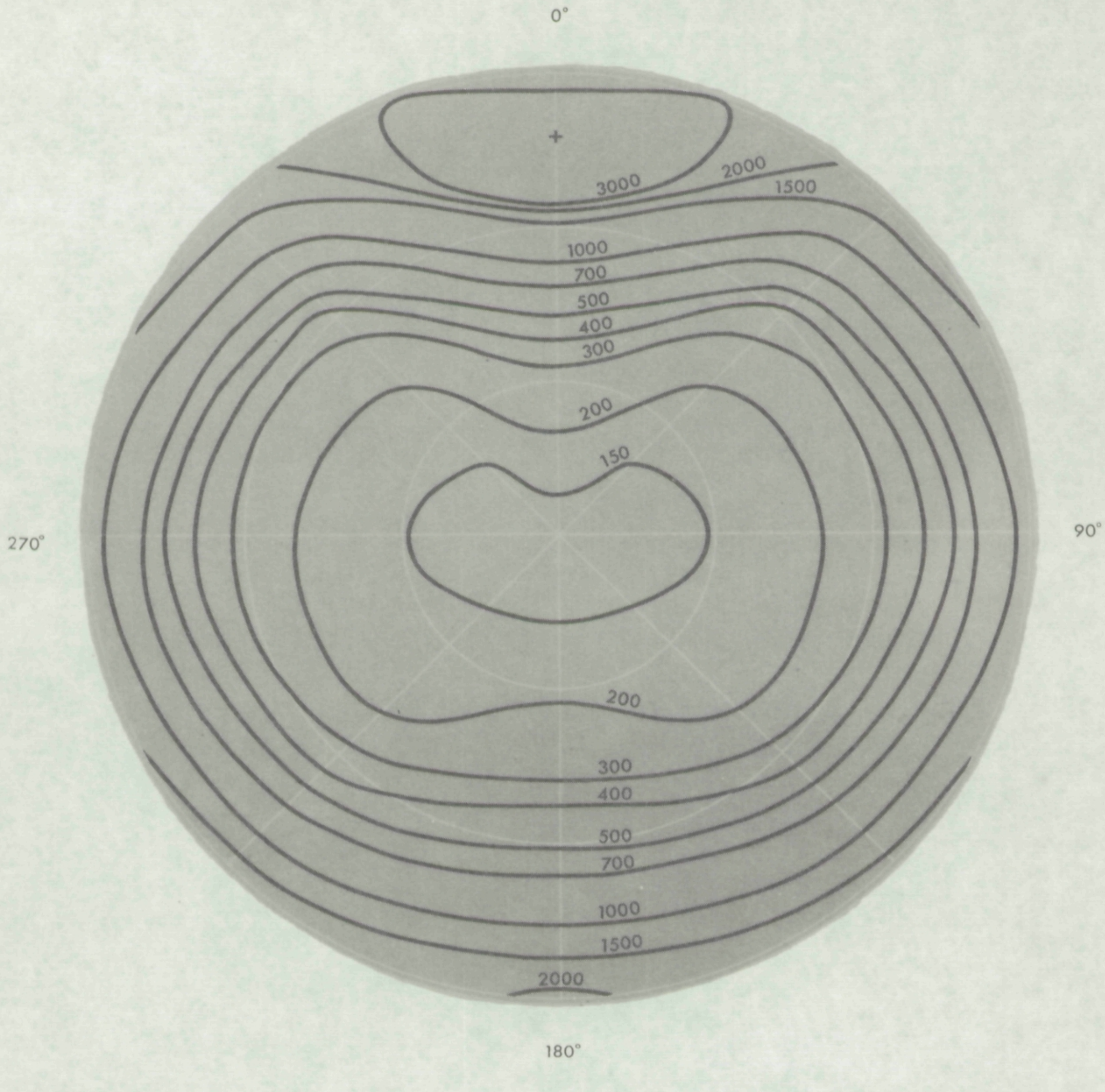

Fig. 7 Lower sky luminance in ft-L. Map depicts the apparent sea luminance at 20,000 feet (6.10 km).

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5 AUTHOR(S) (Last name, first name, initial)

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13 ABSTRACT

Measurements of illuminance at sea level, directional luminous reflectance of certain terrains and objects, atmospheric beam transmittance, and path luminance for a day with an unobscured, low sun are presented. These data are applicable for visibility calculations for downward paths of sight.

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