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NIGHT-SKY RADIANT STERANCE FROM 450 TO 2000 NANOMETERS

Mishri L. Vatsia, et al

Army Electronics Command
Fort Belvoir, Virginia

September 1972

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by

Mishri L. Vatsia
U. Karl Stich
Douglas Dunlap

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U. Karl Stich
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13. ABSTRACT

A ground-based, 3-channel Fourier spectroradiometer with a wave-number resolution of 250 cm^{-1} was used to measure night-sky spectral radiant sterance (radiance) in the 450-nm to 2000-nm wavelength region. The experimental sites were remote locations in Panama, United States, and Canada. Details of night-sky radiation measuring system, calibration equipment, and procedures for data acquisition and analysis are presented. A large number of night-sky radiant sterance spectra recorded under various types of nighttime meteorological environments and moon phases are presented. The results are compared to measurements reported in the literature. The night-sky radiant sterance spectra presented in this work are unique in two respects: (1) they cover the wide wavelength region from 450 nm to 2000 nm; and (2) they were recorded under a large variety of nighttime, atmospheric, optical environments.

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

ECOM-7022

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FROM 450 TO 2000 NANOMETERS

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VISIONICS TECHNICAL AREA
NIGHT VISION LABORATORY

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U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

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SUMMARY

A ground-based, 3-channel, Fourier spectroradiometer with a wave-number resolution of 250 cm^{-1} was used to measure night-sky, spectral radiant sterance (radiance) in the 450-nm to 2000-nm wavelength region. The experimental sites were remote locations in Panama, United States, and Canada. Details of the night-sky radiation-measuring system, calibration equipment, and procedures for data acquisition and analysis are presented. A large number of night-sky radiant-sterance spectra recorded under various types of nighttime meteorological environments and moon phases are presented. The results are compared to measurements reported in the literature. The night-sky radiant sterance spectra presented in this work are unique in two respects: (1) they cover the wide wavelength region from 450 nm to 2000 nm; and (2) they were recorded under a large variety of nighttime, atmospheric, optical environments.

FOREWORD

We wish to acknowledge the general program direction and encouragement by Mr. John Johnson, Director, Visionics Technical Area, Night Vision Laboratory. The Fourier Spectrometers used in this study were fabricated by Block Engineering, Inc., on contract with the Night Vision Laboratory to the specifications and design parameters determined by M. L. Vatsia and the late Mr. Kendall Cooper of Night Vision Laboratory. James R. Martin and James R. Engel of Block Engineering, Inc., provided assistance in operating the instruments at some field sites. Dr. Henry J. Kostkowski, NBS, provided helpful comments on the calibration procedure. The original manuscript was typed by Lou Ann Dobson.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (cont'd)

NIGHT-SKY RADIANT STERANCE

FROM 450 TO 2000 NANOMETERS

I. INTRODUCTION

During 1968, the Atmospheric Optics Team, Night Vision Laboratory, made a series of night-sky spectral radiant sterance* (radiance) measurements in the North American continent at remote locations ranging in latitude from 8° N to 47° N. The main objective of these measurements was to determine basic, night-sky spectral radiant sterance characteristics at ground level and their variations with latitude and various nighttime optical and meteorological conditions such as lunar phase, cloud cover, air temperature, and relative humidity.

Earlier Night Vision Laboratory (NVL) measurements of night-sky spectral radiant sterance from 400 nm to 2000 nm made at a single location in central Virginia during the summer months of 1962 and 1964 using two different experimental spectroradiometers were reported by Johnson and his coworkers.[1] Chamberlain,[2] Roach,[3,4] Krassovsky[5] *et al.*, and McCormac[6,7] have published comprehensive and authoritative literature on the astrogeophysical aspects of nightglow spectra and atmospheric emissions. World-wide photometric measurements of clear daytime and nighttime, natural, luminous incidance (illuminance) were made by Dayton Brown[8] and his colleagues during the 1943-1947

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*For radiometric nomenclature, the reader is referred to the proposed MIL Standard for Infrared Terms and Definitions, Part 1, Appendix C, of Final Report QL-TR-71-7, MICOM Contract DAAH01-71-C-0433, Ford-Philco Corporation, Aeronutronic Division, Newport Beach, California 92663 (1971).

[1]J. Johnson, K. Cooper, E. Bienz, and J. Bunor, *Optical Properties of Targets and Backgrounds at Night*, Report 1838, US Army, ERDL, Fort Belvoir, Virginia (1965).

[2]J. W. Chamberlain, *Physics of the Aurora and Airglow*, Academic Press, New York and London (1961).

[3]F. E. Roach, *The Nightglow, Advances in Electronics and Electron Physics*, Volume 18, 1, Academic Press, New York and London (1963).

[4]F. E. Roach, "The Light of the Night Sky: Astronomical, Interplanetary and Geophysical," *Space Science Reviews* 3 512-540 (1964).

[5]V. I. Krossovosky, N. N. Shefov, and V. I. Yarin, *Planetary and Space Science* 9, 883 (1962).

[6]B. M. McCormac and A. Omholt, editors, *Atmospheric Emissions*, Van Nostrand Reinhold Company, New York (1969).

[7]B. M. McCormac, editor, *The Radiating Atmosphere*, D. Reidel Publishing Company, Dordrecht-Holland (1971).

[8]Dayton R. E. Brown, *Natural Illumination Charts*, Report No. 374-1, Department of the Navy, Bureau of Ships, Washington, D. C. (1952).

period. Biberman[9] *et al.* have computed levels of nocturnal, luminous incidance for clear atmospheric conditions and have reproduced Dayton Brown's report as an appendix to their paper. Harrison and Jones[10] and D. Pardy[11] have reported near-infrared, night-sky spectra, whereas Morley[12] has made ground-level, total and spectral incidance measurements in the visible spectrum. Höhn and Maffeo[13] have made observations of night-sky radiant sterance spectra from 500 nm to 1100 nm. Observations of diurnal (or nocturnal), seasonal, and latitudinal variations of nightglow have been reported by Davis and Smith,[14] Greenspan and Woodman,[15] and Markham and Anctil.[16 17] Broadfoot and Kendall[18] have recently made high-resolution, airglow spectrum measurements in the wavelength range from 310 nm to 1000 nm at an altitude of approximately 2 kilometers above sea level. Our work includes a series of observations of absolute, night-sky radiant sterance made at ground level under a variety of radiant incidance (irradiance) and meteorological conditions covering the entire spectral range from 450 nm to 2000 nm.

II. INSTRUMENTATION

Night Vision Laboratory's night-sky-radiation-measuring system consists of a 3-channel Fourier spectroradiometer complete with associated electronics and data-acquisition system installed in a mobile van. The van is equipped with a 6-kilowatt, 110-V, 60-Hz electric generator, water, bath, cooking, sleeping, living, and working facilities sufficient for two operators for 1 week's field operation. Figure 1 shows the night-sky radiation-measuring system. Figure 2 shows the Atmospheric Optics Mobile

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[9] L. M. Biberman, L. Dunkelman, M. L. Finckett, and R. G. Finke, *Levels of Nocturnal Illumination*, Research Paper P-232, Institute for Defense Analysis, Arlington, Virginia (1966); and L. M. Biberman and S. Nudelman, editors, *Photoelectronic Imaging Devices*, Volume 1, Plenum Press, New York (1971).

[10] A. W. Harrison and A. Vallance Jones, *Journal of Atmospheric and Terrestrial Physics, 11*, 192 (1957).

[11] D. Pardy, *Emission from the Night Sky in the 1 to 2 Micron Spectral Band*, Report No. 1147, Signals Research & Development Establishment, Christchurch, U. K. (1965).

[12] G. A. Morley, *Measurements of Ground Level Irradiance from the Night Sky*, Technical Report 537/65 Canadian Armament Research and Development Establishment, Quebec, Canada (1965).

[13] D. H. Höhn and G. F. Maffeo, *Spectral Radiance of the Clear and Overcast Night Sky at Wavelengths between 0.5 and 1.1 Micron*, NVL T-1924-68R, Technical Information and Library Branch, USAMERDC, Fort Belvoir, Virginia 22060 (1968).

[14] T. N. Davis and L. L. Smith, *Jour. of Geophysical Research, 70*, 1127 (1965).

[15] J. A. Greenspan and J. H. Woodman, *Journal of Atmospheric and Terrestrial Physics, 29*, 239 (1967).

[16] T. P. Markham and R. E. Anctil, *Journal of Atmospheric and Terrestrial Physics, 29*, 897 (1967).

[17] T. P. Markham and R. E. Anctil, *Journal of Geophysical Research, 71*, 997 (1966).

[18] A. L. Broadfoot and K. R. Kendall, *Journal of Geophysical Research, Space Physics, 73*, 426 (1968).

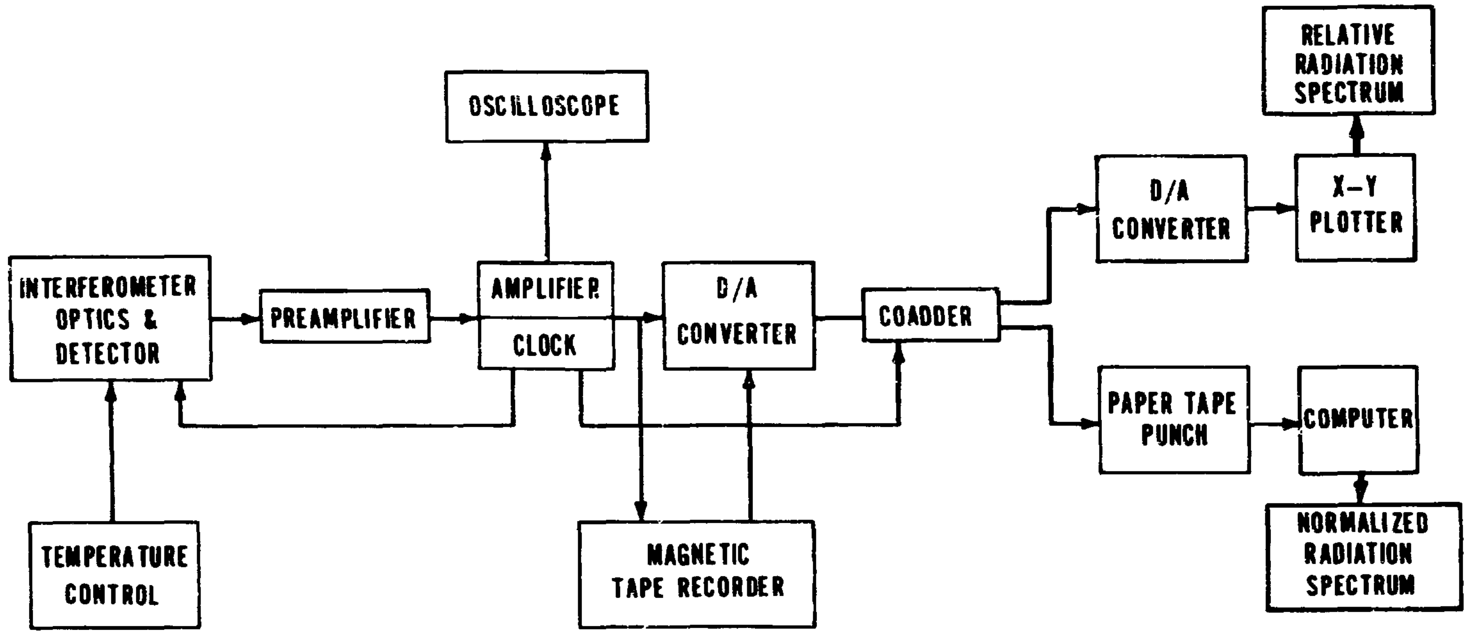

Fig. 1. The nighttime radiation measuring system.

Fig. 2. The Atmospheric Optics Mobile Laboratory showing the three optical heads of the Fourier spectroradiometer raised on the hydraulic platform.

Laboratory with the three optical heads of the Fourier spectroradiometer raised on a hydraulic platform through a hatch in the roof of the van. The hydraulic platform has a retractable foot which is lowered to the ground in order to provide a stable platform isolated, as much as possible, from the electric generator and other vibrations in the van. The Fourier spectroradiometer system covers the wavelength region from 400 nm to 2000 nm in three overlapping ranges. An uncooled photomultiplier tube, type EMR 541E, with S-20 spectral response, is employed for the 400 nm to 800 nm range, a Dry Ice cooled (-56.6° C) silicon (Si) cell for the 550 nm to 1100 nm range, and a Dry Ice cooled lead sulfide (PbS) detector for the 900 nm to 2000 nm range. Each of the three spectroradiometer channels contains a 1.6-cm-aperture Michelson Interferometer with appropriate optics and electronics including low-noise, solid-state preamplifiers and power amplifiers, detector bias power supply, and a temperature-control unit. The data display, acquisition, and reduction system consists of a dual-beam oscilloscope, a magnetic tape recorder, a coadder, a spectrum analyzer, an x-y plotter, a paper-tape punch, a frequency counter, and simple meteorological instruments such as an anemometer and an electric hygrometer/thermometer. A temperature-control system automatically controls the input current to the heating elements which maintain the temperature of the interferometer optical "cube" at a constant value of 33° C in order to maintain optical and mechanical stability of the delicate interferometer in the presence of ambient temperature fluctuations. The coadder is a time-averaging computer that increases the signal-to-noise ratio of the spectra. The input signals are sequentially digitized and stored in the coadder core memory. Each series of samples is initiated by a triggering pulse generated at the beginning of each interferometer scan.

III. ELEMENTARY PRINCIPLE OF FOURIER SPECTROSCOPY

When radiation from a source of radiant sterance distribution $L(\nu)\,d\nu$ passes through a 2-beam Michelson interferometer, the original beam is divided into two separate beams of equal amplitude and then is recombined after travelling different paths as shown in Fig. 3a. The radiation reaching the center of the fringe system produces a signal $S_o(x)$ as a function of optical path difference x between the interfering beams given by the following equation:[19 20 21]

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[19] G. A. Vanasse and H. Sakai, *Progress in Optics*, Volume VI, 261, North-Holland Publishing Company (1967).

[20] K. M. Baird and G. R. Hanes, "Interferometers," in *Applied Optics and Optical Engineering*, edited by R. Kingslake, Volume IV, Academic Press, New York (1967).

[21] G. A. Vanasse, A. T. Stair, Jr., and D. J. Baker, editors, Aspen International Conference on Fourier Spectroscopy, 1970 AFCRL-71-0019 Air Froce Cambridge Research Laboratories, L. G. Hanscom Field, Bedford, Massachusetts (1971).

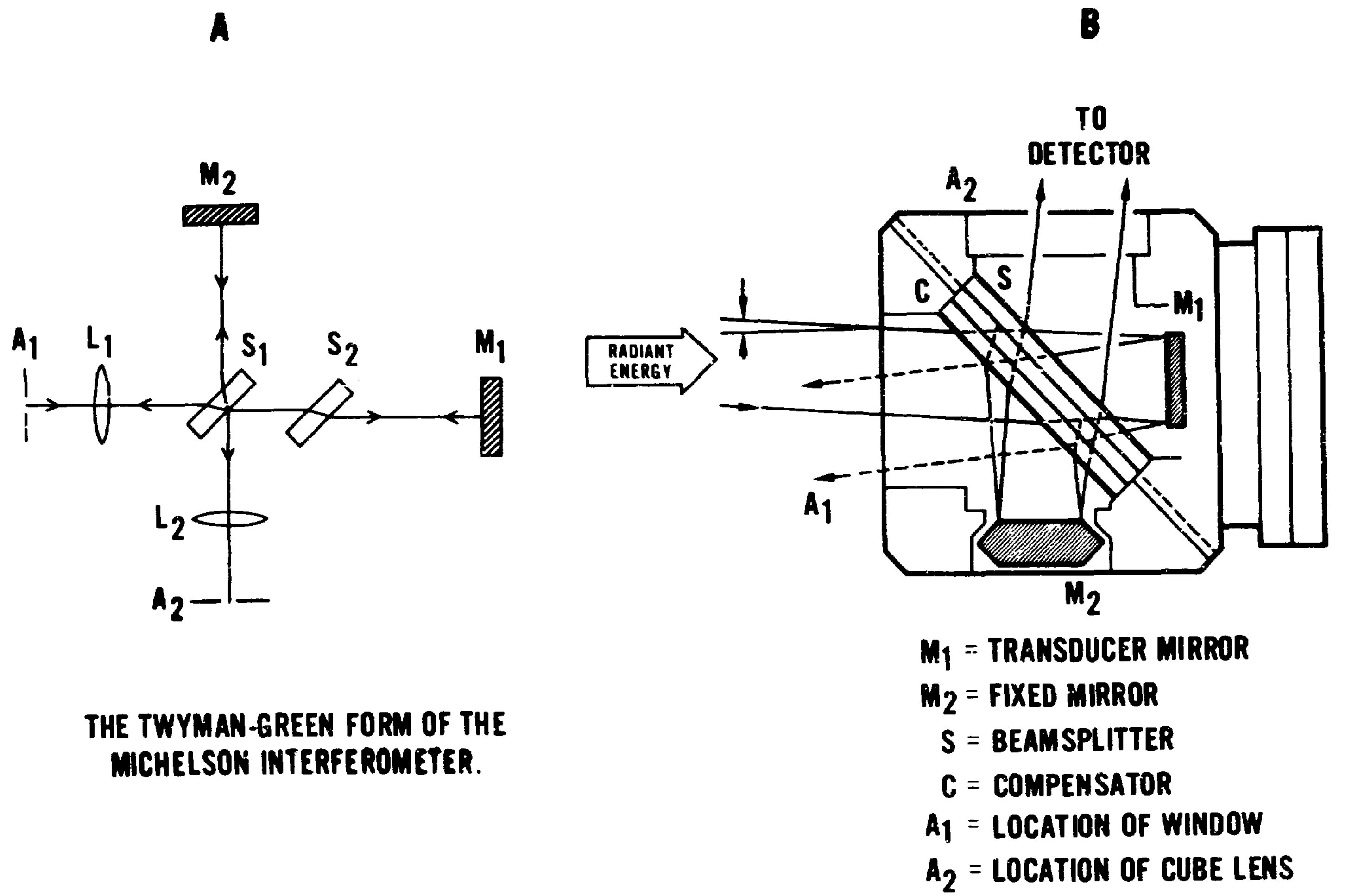

Fig. 3. Michelson interferometer optical system: (A) Twyman-Green type, and (B) engineering layout (Block Engineering).

$$S_o(x) = L(\nu)\,(1 + \cos 2\pi\,\nu\,x)\,d\nu \qquad (1)$$

where ν cm^{-1} is the wavenumber of the monochromatic radiation incident on the detector. The output is modulated at a frequency νx. Polychromatic radiation will produce a signal given by the integral of the above equation:

$$S(x) = \int_o^{\nu_m} L(\nu)\,(1 + \cos 2\pi\,\nu\,x)\,d\nu \qquad (2)$$

the interferogram I(x) is given by

$$I(x) = S(x) - \int_o^{\infty} L(\nu)\,d\nu \qquad (3)$$

combining equations (2) and (3) gives

$$I(x) = \int_o^{\infty} L(\nu)\cos 2\pi\,\nu\,x\,d\nu. \qquad (4)$$

When I(x) is symmetric, the spectrum $L(\nu)$ is given by

$$L(\nu) = 2\int_o^{\infty} I(x)\cos 2\pi\,\nu\,x\,dx. \qquad (5)$$

If the interferogram is not symmetric about the zero point or if there is a finite displacement D of the moving mirror, the spectrum is computed from both cosine and sine terms using the relations:

$$L_c(\nu) = \int_{-D}^{D} I(x)\cos(2\pi\,\nu\,x)\,dx \qquad (6)$$

$$L_s(\nu) = \int_{-D}^{D} I(x)\sin(2\pi\,\nu\,x)\,dx \qquad (7)$$

and the spectrum is given by

$$L(\nu) = (L_c^2 + L_s^2)^{1/2}. \qquad (8)$$

The phase relation is given by

$$\varphi = \arctan (L_s/L_c). \qquad (9)$$

The phase can be set equal to zero at the point of zero path difference. A change in the direction of net energy flux will then produce a 180° phase shift.

Thus, the correct spectrum of the incident radiation is obtained through a Fourier transformation of the interferogram represented by the output of the detector. The electrical frequency in the output interferogram signal is generated by varying the path difference between the two beams in the interferometer. If this path difference is changed at a rate of v cm/sec, the frequency f, sec^{-1}, of electrical signal due to radiation of wavenumber ν cm^{-1} is given by

$$f = \nu\, v. \qquad (10)$$

Figure 3b shows a schematic engineering diagram of the Michelson interferometer optical system. Mirror M_1 is driven by an electromagnetic transducer operated by a sweep pulse.

A 2-beam Fourier spectrometer has a large energy-gathering capacity. This is known as throughput gain G. The radiant flux available at the detector is given by

$$\Phi = T\, G\, L_\nu \qquad (11)$$

where T is the transmittance of the system; L_ν, the radiant sterance of the source; and G, the quantity known as throughput. If the cross-sectional area of the output beam is A, and Ω, the solid angle subtended by the exit aperture, the throughput G is defined as

$$G = A\, \Omega \qquad (12)$$

For a Michelson interferometer as used in Fourier spectroscopy, the solid angle of the incident radiation is given by[22]

$$\Omega = \pi / \nu\, x \qquad (13)$$

where x is the optical path difference between the interfering beams in the interferometer. The Michelson interferometer resolution $\delta\nu$ and its resolving power R are defined as

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[22] G. A. Vanasse, A. T. Stair, Jr., and D. J. Baker, editors, Aspen International Conference on Fourier Spectroscopy, 1970 AFCRL-71-0019, Air Force Cambridge Laboratories, L. G. Hanscom Field, Bedford, Massachusetts (1971).

$$\delta\nu = 1/2x, \tag{14}$$

and
$$R = \nu / \Delta \nu \tag{15}$$

Combining equations (13), (14), and (15) gives

$$\Omega = 2\pi / R. \tag{16}$$

Substituting from equations (12) and (16) into (11) yields

$$\Phi = 2\pi \, L_\nu \; T A / R \tag{17}$$

or
$$\Phi R = 2\pi \, L_\nu \; T A. \tag{18}$$

Equation (18) indicates that for a Fourier spectrometer the product ΦR is a constant of the system. If we attempt to obtain higher resolution R, the energy flux available for detection decreases. The Table shows instrument resolution, field of view, and noise-equivalent input for each detector.

INSTRUMENT PARAMETERS

	RESOLUTION cm^{-1}	FIELD OF VIEW STERADIAN	NESR @ λ $Wcm^{-2}STER^{-1}10\ nm^{-1}$ [S/N = 1]
PMT	236	3.6×10^{-2}	5.9×10^{-16} @ 600 nm
Si	254	2.6×10^{-2}	9.26×10^{-14} @ 900 nm
PbS	230	2.2×10^{-2}	2.92×10^{-13} @ 2000 nm
			9.5×10^{-12} @ 1000 nm

The wavelength resolution in angstroms of the instrument at a wavelength λ in micrometers and wavenumber resolution $\Delta\nu$ in cm^{-1} is given by the relation:

$$\Delta\lambda(A) = [\lambda(\mu m)]^2 \; [\Delta\nu\,(cm^{-1})] \tag{19}$$

and the wavelength of radiation in micrometers (μm) is related to the corresponding wavenumber (cm^{-1}) by the relation:

$$\lambda\,(\mu m) = 10^4/\Delta\nu\,(cm^{-1}). \qquad (20)$$

IV. CALIBRATION EQUIPMENT AND PROCEDURE

1. **Wavelength Calibration.** A miniature helium lamp, type A-267 (manufactured by Signal Lite, Inc., 1933, Heck Ave., Neptune, N. J.), operating at 110-V, 60-Hz was placed at a fixed distance in front of the entrance aperture of each interferometer. Appropriate neutral density filters were used to adjust the level of radiation incident on each detector. The spectrogram of helium radiation provided a cross check on the alignment of the optical system of each interferometer optical system. For a properly, optically aligned interferometer, the ratios of the strengths of the known spectral lines in helium spectrum maintain a fairly constant value. The spectral lines of helium used for wavelength calibration and alignment purposes are: 2058 nm and 1083 nm for the PbS detector, 1083 nm and 587.6 nm for the Si detector, and 706.5 nm and 388.8 nm for the Photomultiplier Tube.

2. **Spectral Radiant Sterance Calibration.** A tungsten lamp (Type General Electric 30 A/T24/7 with SR-8A ribbon filament) was used as a secondary radiation source for field calibration. The primary calibration lamp was an Eppley Standard of Spectral Radiant Incidance (Irradiance), EPI-1305, a General Electric 1000-Watt 8.3 Ampere Quartzline lamp. The spectral radiant incidance of the secondary lamp was calibrated by comparison with that of the primary standard.

V. SPECTRAL DATA ACQUISITION AND COMPUTATION

In the field, night-sky radiation spectra were recorded by raising the hydraulic platform of the spectrometers above the roof through a hatch (Fig. 2). The apparent radiant sterance of the night sky as observed from the ground was measured by recording the radiant sterance of a ground-based flat diffuse blotter surface irradiated by the night sky. The normal to the diffuse reflector was facing due North at a zenith angle of 45° in all these measurements. The spectrometers were located horizontally at a distance of 0.8 meter from the diffuse reflector completely over-filling the field of view of each spectrometer. Thus, the instruments measured radiation received from a part of the hemisphere. The results include normalization to the whole hemispheric radiation measured at normal incidence. The absolute radiant sterance has an estimated error of about ± 15% due to the calibration and measuring procedure. The interferograms were recorded on magnetic and paper tapes and later read into a computer where the Fourier transform of an interferogram resulted in the corresponding radiation spectrum. An interferogram scan was recorded in 175 milliseconds. Each observation involved integration of 3000 interferogram scans over a period of approximately 10 minutes. The output of the three detectors was simultaneously recorded on three channels of the magnetic tape recorder. The fourth channel of the magnetic tape was used for audio identification of the spectral records for identification of data. Spectral information recorded on three spectral channels of the magnetic tape was played back into the coadder, one channel at a time. The coadder accumulated each interferogram as it read the magnetic tape and stored the sum. There are 512 words in the coadder and 16 bits in each word. The output signal of the coadder was displayed on the oscilloscope in real time and read out after each integration period on a paper punch tape for computer processing. The output of the coadder was also fed into a spectrum analyzer whose output was recorded on an x-y plotter, resulting in a permanent analog record of the spectrum for quick checking of results. Accurate spectral analysis required the use of a large digital computer. A Univac 1108 computer system was used to process spectral data by the Cooley-Tukey Fast Fourier Transform method,[23] and a Calcomp plotter was used for graphing the spectra. Figure 4 illustrates the relative spectral response of the three detectors. The photomultiplier and silicon detectors were fairly sensitive, but the response of the lead sulfide detector around the 1100-nm wavelength region was far from satisfactory (see Table for NESR values). The radiation source used for field calibration had a low output below 450 nm which rendered the calibration of night-sky spectra shorter than 450 nm rather difficult.

VI. RESULTS

1. **United States Measurements.** Soon after the Atmospheric Optics Mobile Laboratory was completed in early 1968, preliminary observations of the spectral radiant sterance of the night-sky were made at Camp A. P. Hill, Virginia (Latitude 38° 09′ N, Longitude 77° 21′ W), and at Cooper's Lake, Nashville, North Carolina (Latitude N 35° 52.40′, Longitude W 77° 57.92′, Elevation 58 meters above sea level). Figure 5 shows night-sky radiant sterance spectra recorded at Camp A. P. Hill, Virginia, on 22 February and 15 March, 1968. Spectra numbered 1, 2, and 3 correspond to moonlight illumination with various cloud conditions and angles of elevation of the moon. As expected, the magnitude of radiant sterance for maximum lunar elevation and least cloud cover is the highest throughout the spectral range of observation. Spectrum No. 3 illustrates that there is nearly a uniform attenuation under a complete overcast condition throughout the spectral range of observation. Spectrum No. 4 was recorded at the same site under a clear, moonless night-sky condition on 22 February 1968. Figure 6 shows two typical radiant sterance spectra recorded under a clear, moonless night sky at Cooper's

[23] J. W. Cooley and J. W. Tukey, *Mathematics of Computation, 19,* 297 (1965).

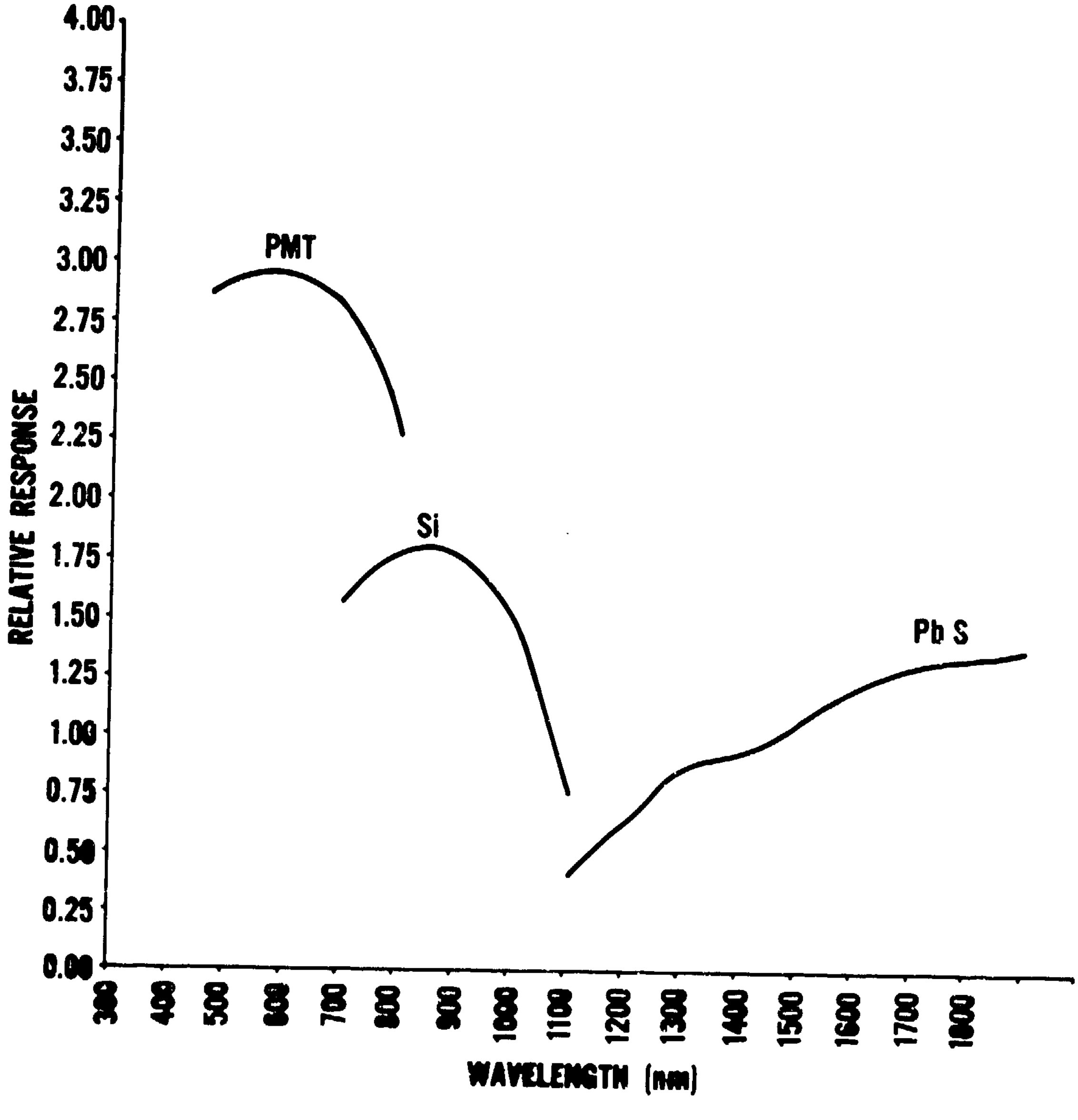

Fig. 4. Relative spectral response of three detector systems.

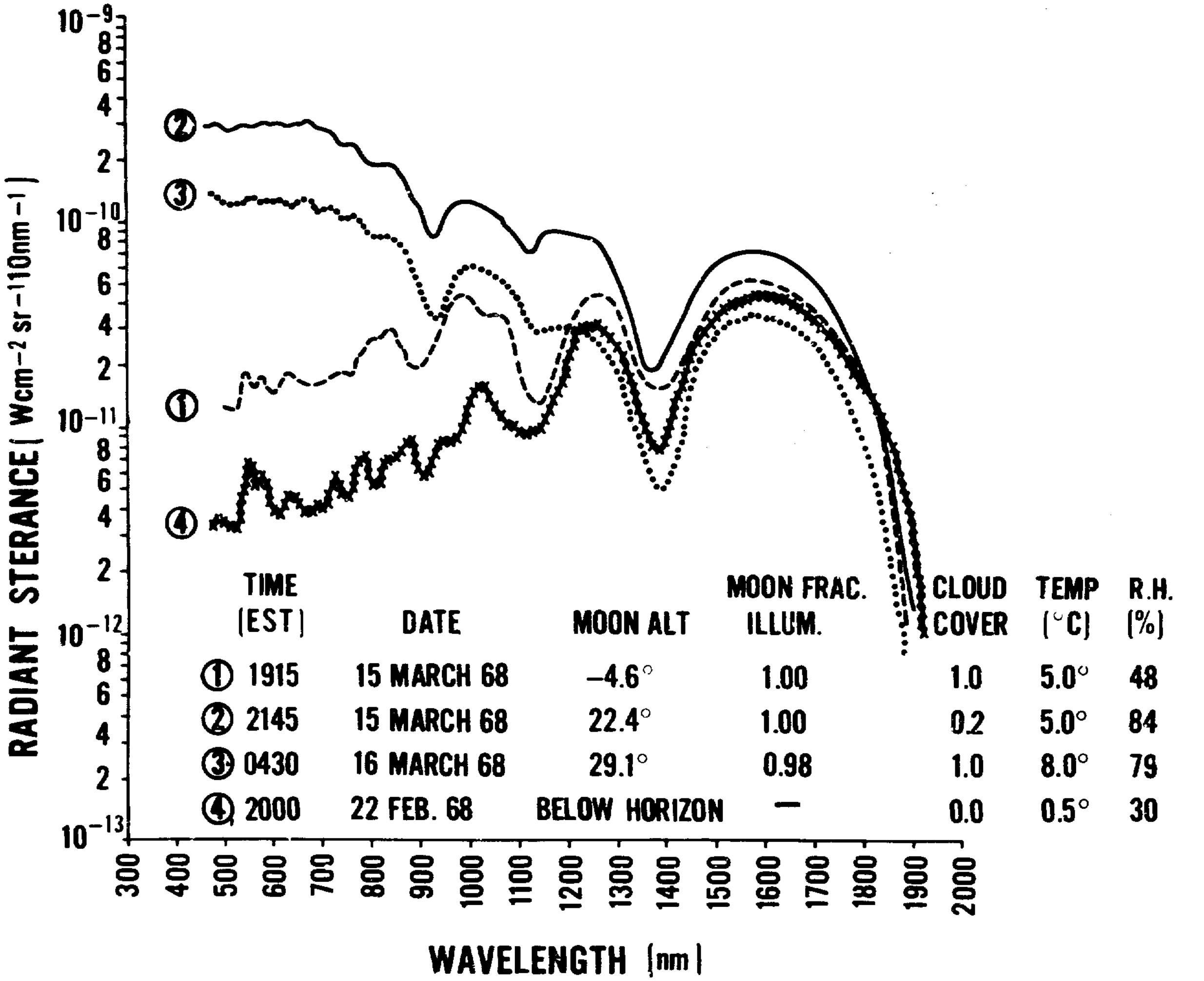

Fig. 5. Night-sky radiant sterance spectra recorded at Camp A. P. Hill, Virginia on February 22, 1968 and March 15-16, 1968.

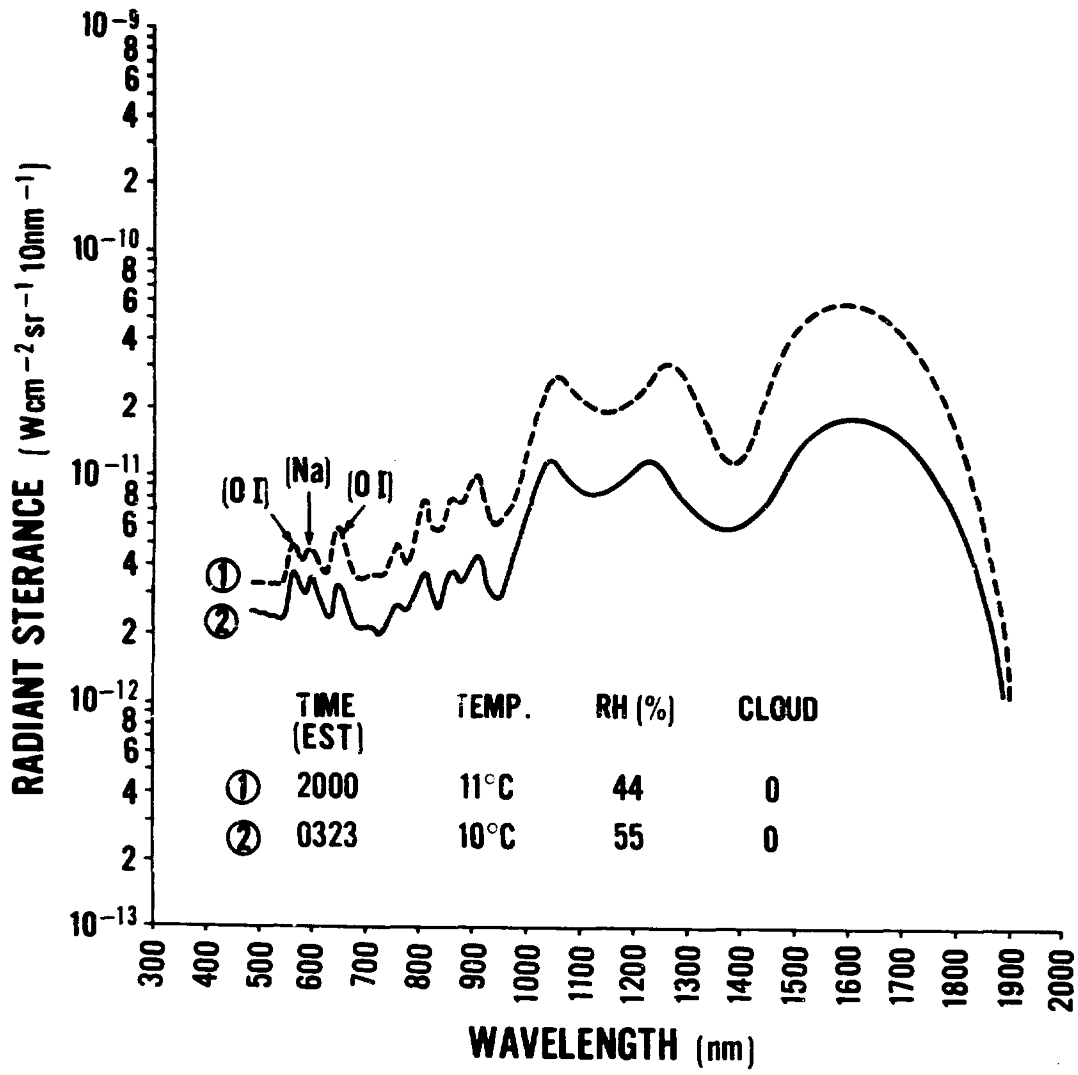

Fig. 6. Night-sky radiant sterance spectra recorded at Cooper's Lake, Nashville, N. C., March 26, 1968.

Lake, Nashville, North Carolina. The observation site at Cooper's Lake had a partial canopy of tall trees. Spectrum No. 1 recorded at 2000 hrs represents typical radiant sterance levels during early hours of the night. Spectrum No. 2 represents nearly the lowest clear night-sky radiant sterance level recorded anywhere in our observations.

2. **Panama Measurements.** In May 1968 the Atmospheric Optics Mobile Laboratory was airlifted to Panama. The measurement site was a remote location near Rio Hato, Panama (8° 20′ N latitude and 80° W longitude). This site was relatively dry compared to an average, rather wet Panamanian summer climate. With great difficulty, it was possible to record night-sky spectra on about 10 nights in the 8 weeks of stay on the site due to frequently inclement weather. It was a typical tropical climate characterized by high relative humidity and high air temperature with partial-to-complete overcast sky conditions. Figure 7 shows three night-sky, radiant sterance spectra recorded at Rio Hato, Panama, on May 26, 1968, on a moonless night with various degrees of cloud cover. Figure 8 shows four spectra recorded at Rio Hato on June 6, 1968, for different elevations of the moon and a uniformly light cloud coverage under an almost stable meteorological condition. Spectra numbered 1, 2, and 3 show the expected fall in radiance with lunar elevation. Spectrum No. 4 exhibits an unusual absorption in the visible region of spectrum near 600 nm just before the morning twilight. This spectrum does correspond to the maximum optical air mass traversed by solar radiation probably suffering multiple reflections between the clouds and various regions of different media of refraction before arrival at the instrument aperture. Figure 9 shows two spectra recorded at Rio Hato, Panama, on June 14, 1968, one before and the other after moonrise, with 60 to 80 percent cloud cover.

3. **Canada Measurements.** During October 1968, the Atmospheric Optics Mobile Laboratory was taken to Quebec, Canada, on the invitation of the Canadian Armament Research and Development Establishment. The experimental site found after a long and difficult search for a remote location free of any artificial illumination was Lake Montauban in Quebec Province, Canada. The coordinates of the site are 46° 53.1′ North latitude, 72° 9.7′ West longitude, and 182 meters elevation above sea level. The measurement period covered the third and fourth quarters of the lunar phase with a variety of meteorological conditions ranging from all-night clear, partial cloudy, to all-night overcast sky, accompanied with comparatively high relative humidity. The air temperature during nights varied from 19° C to 0° C. The lake was surrounded by tall evergreen and deciduous trees. The shore clearance near the experimental site was about 200 meters. The mobile laboratory was located on the east side of the lake where the lake width was approximately 2 kilometers. Figures 10 through 15 show night-sky radiant sterance spectra recorded at Lake Montauban on six nights. The earlier part of the Lake Montauban observations were made in moonlight illumination conditions with various types of cloud cover, while the observations on the last night were made under moonless, night-sky illumination with a complete overcast sky condition.

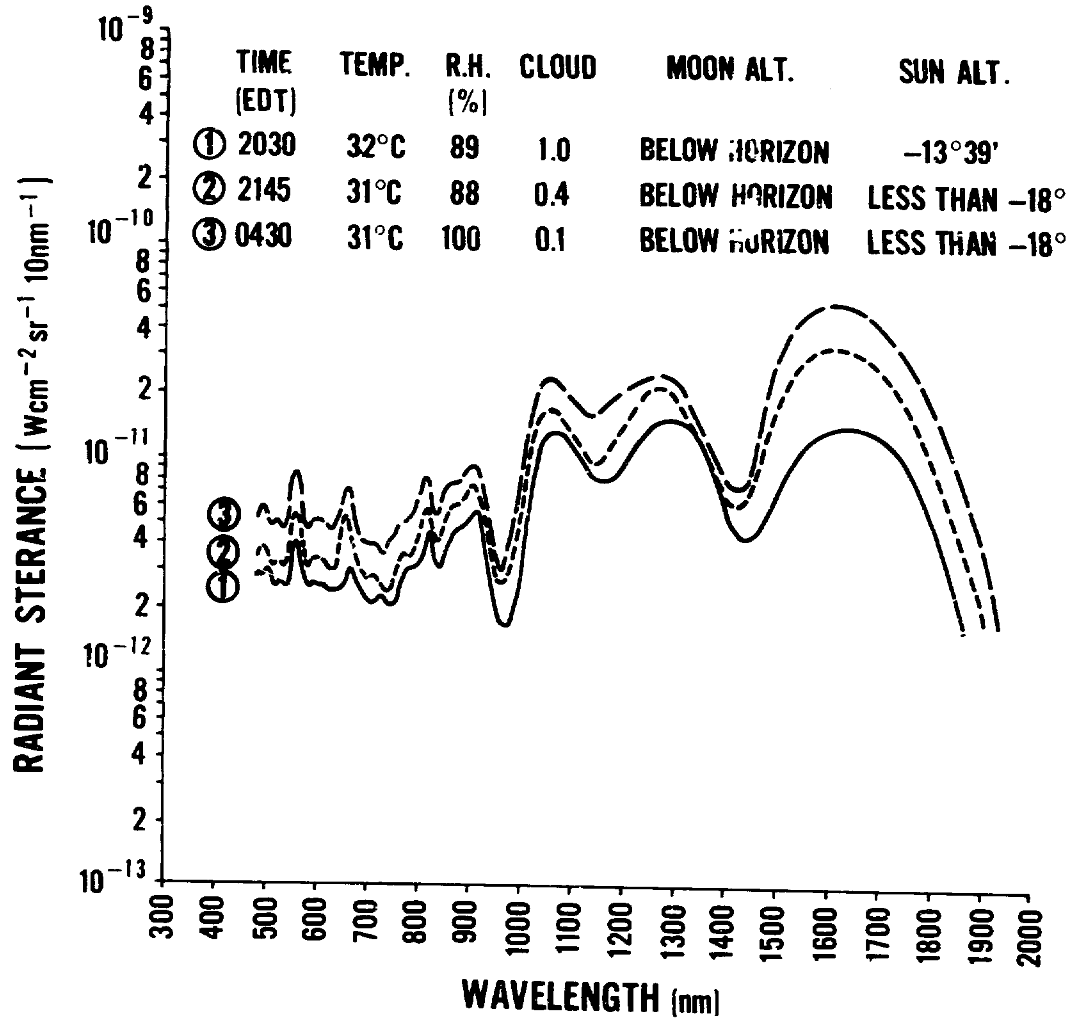

Fig. 7. Night-sky radiant sterance spectra recorded at Rio Hato, Panama, on May 26-27, 1968.

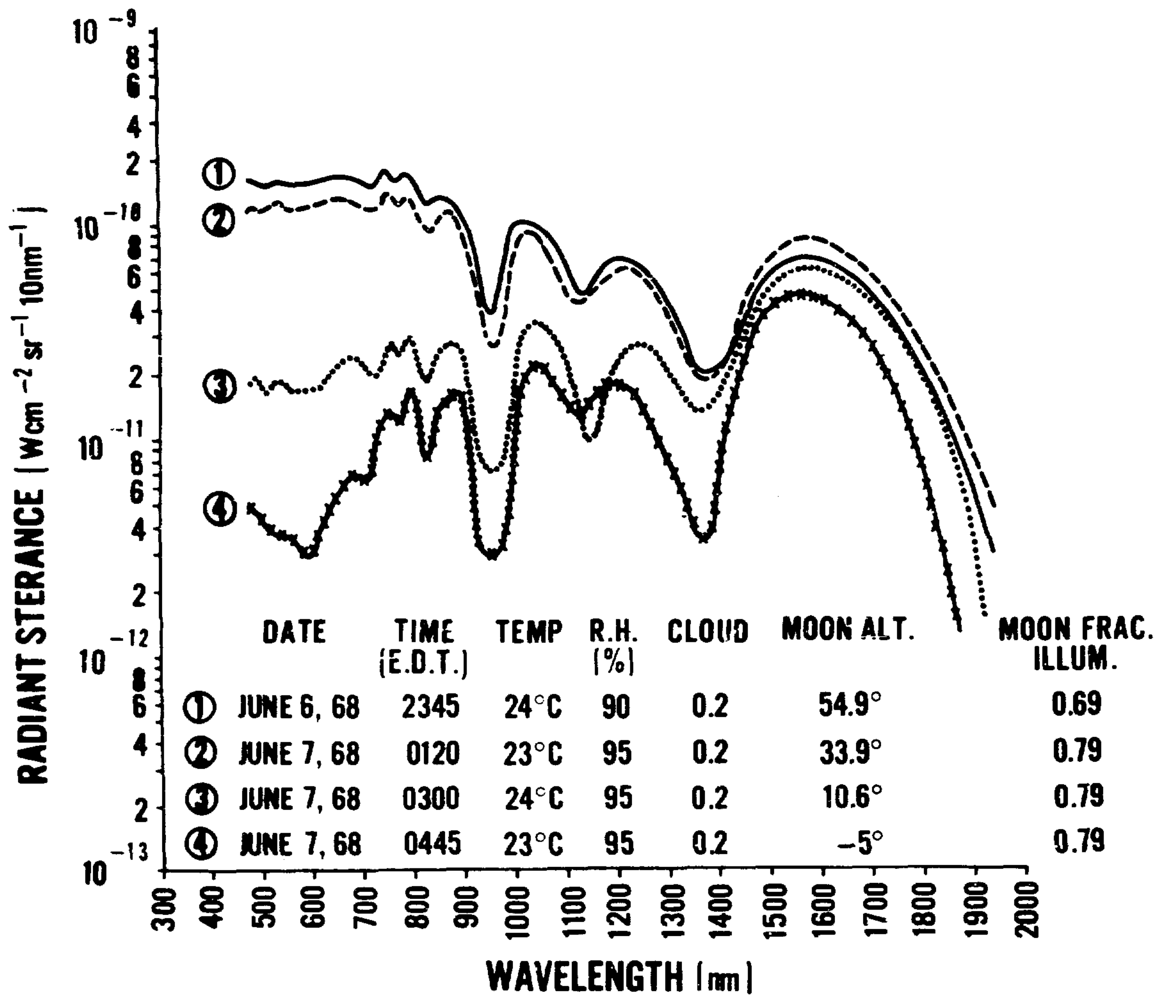

Fig. 8. Night-sky radiant sterance spectra recorded at Rio Hato, Panama, on June 6-7, 1968.

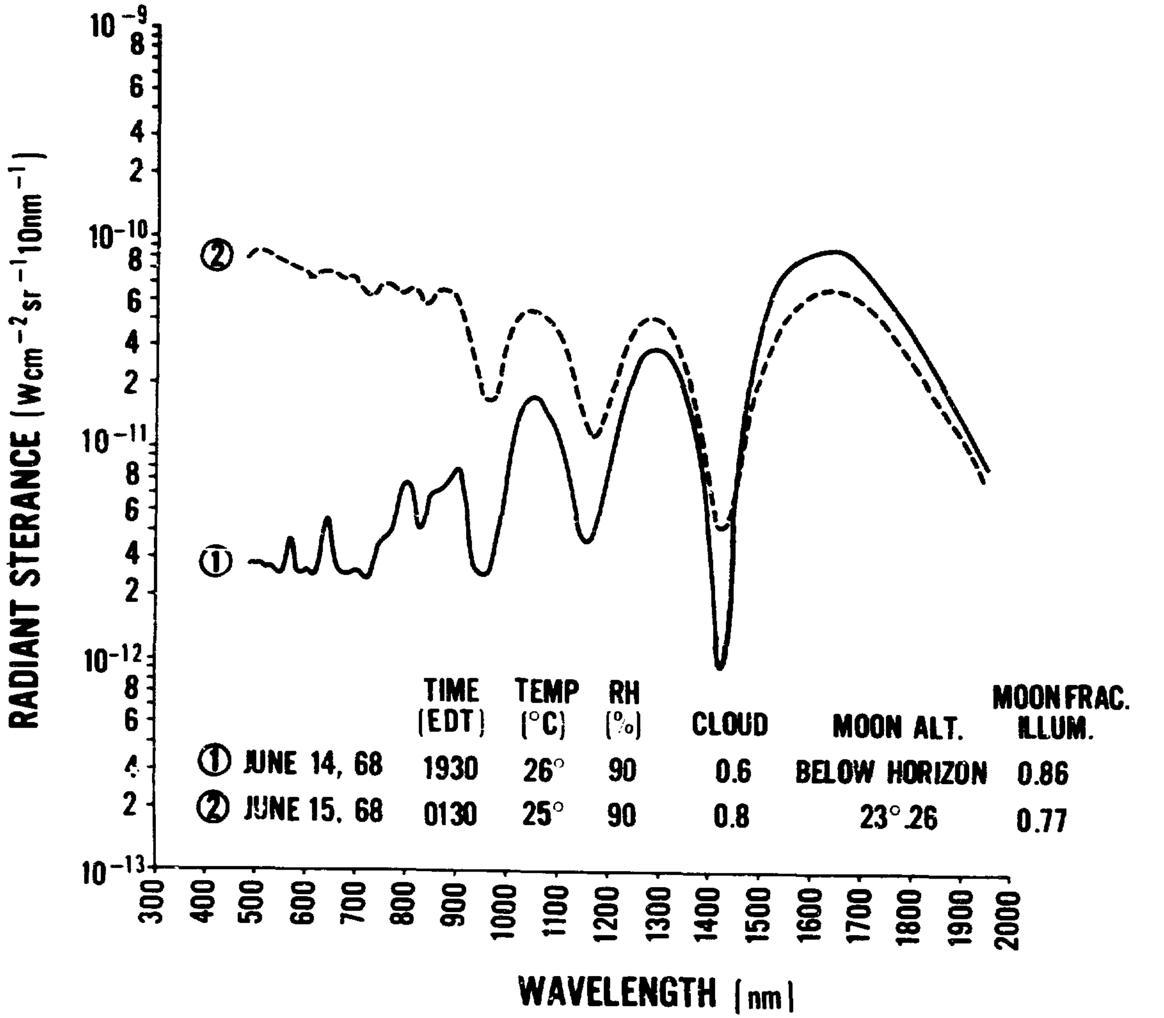

Fig. 9. Night-sky radiant sterance spectra recorded at Rio Hato, Panama, on June 14-15, 1968.

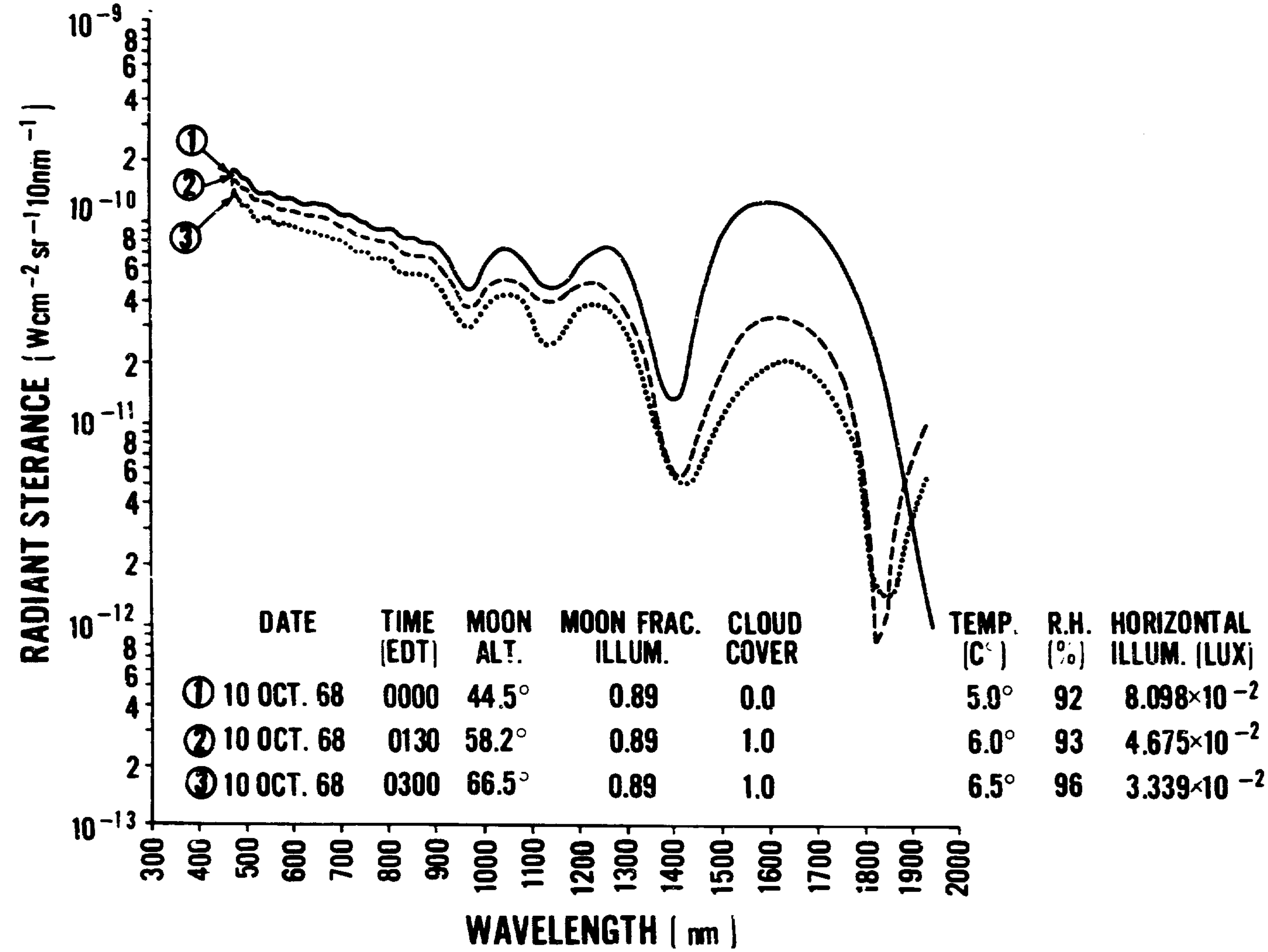

Fig. 10. Night-sky radiant sterance spectra recorded at Lake Montauban, Canada, on October 10, 1968.

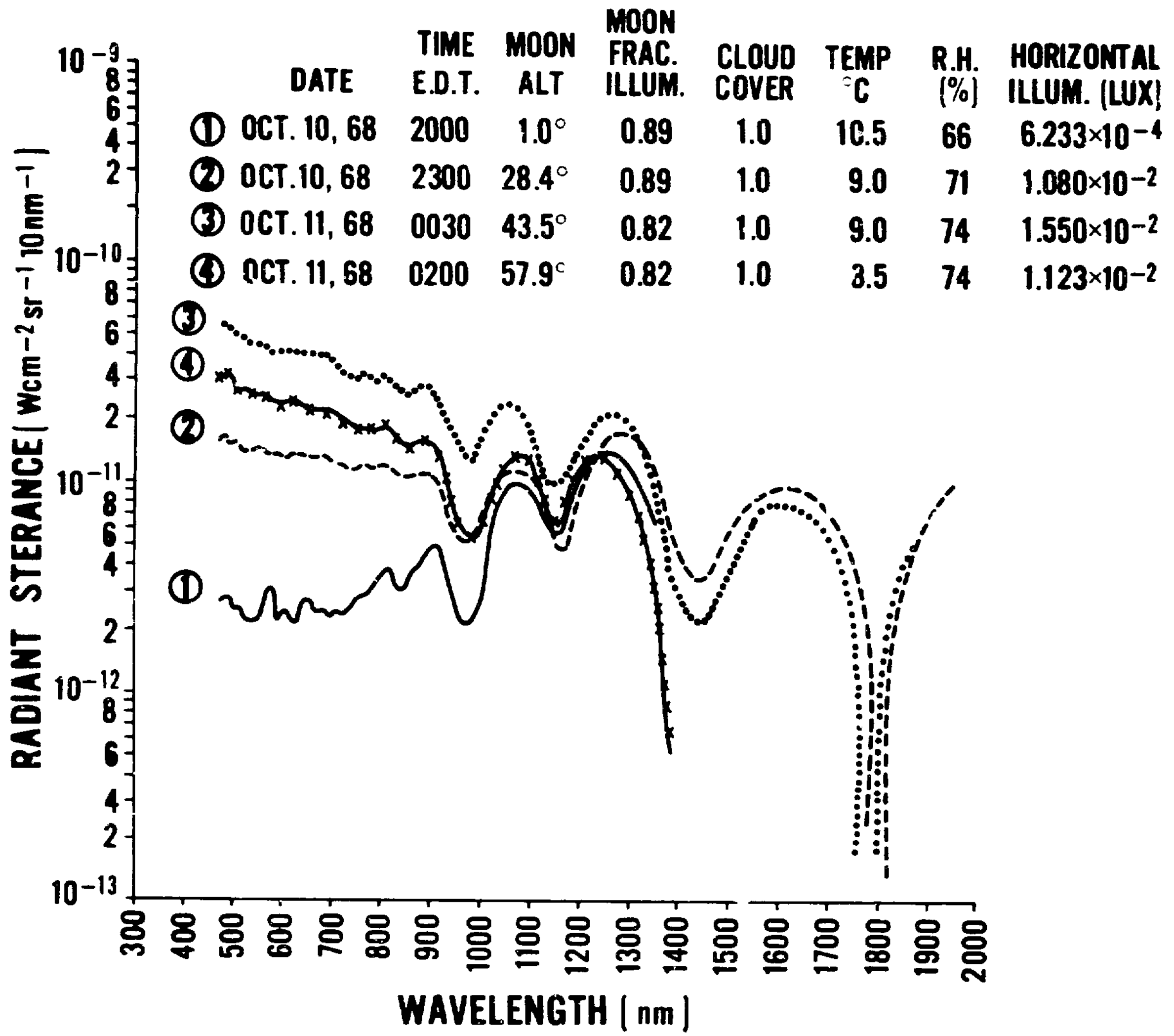

Fig. 11. Night-sky radiant sterance spectra recorded at Lake Montauban, Canada, on October 10-11, 1968.

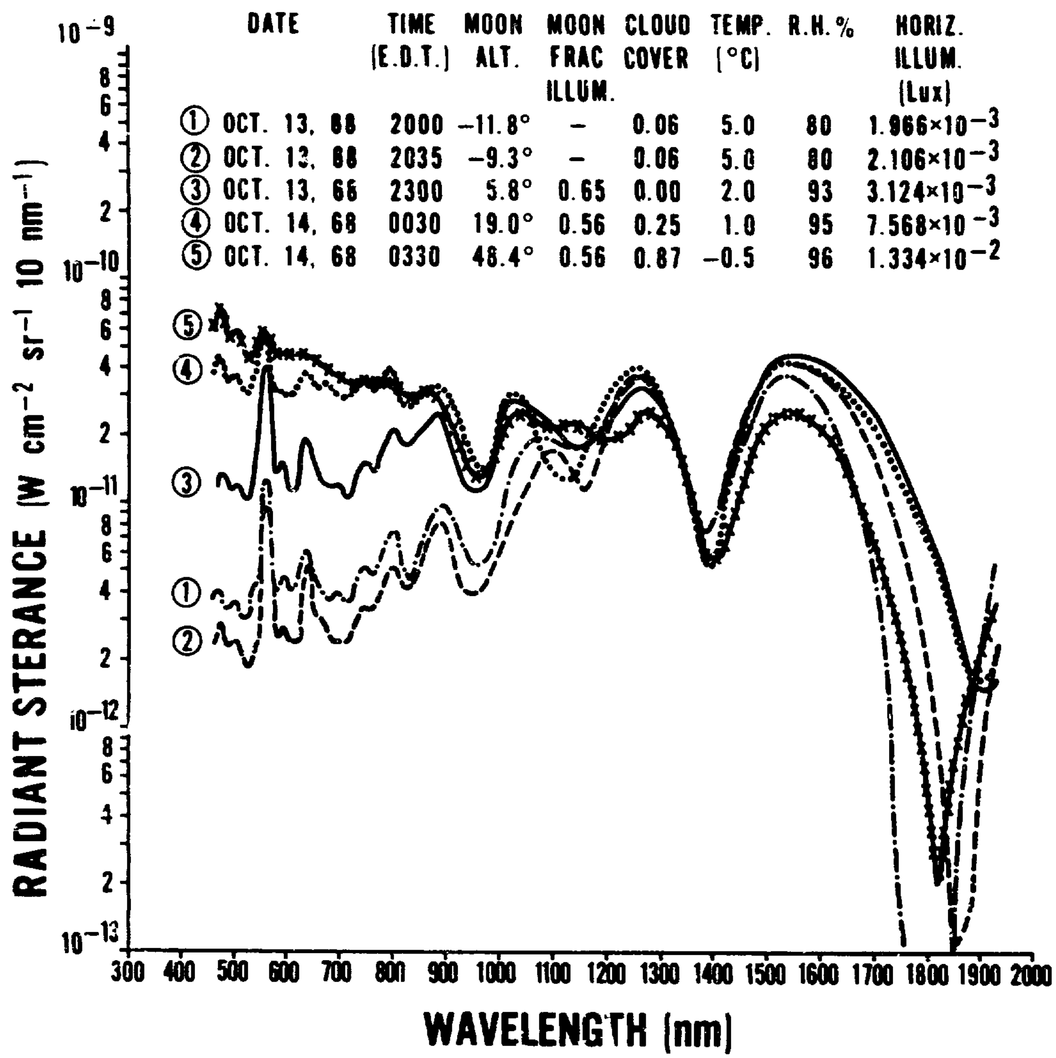

Fig. 12. Night-sky radiant sterance spectra recorded at Lake Montauban, Canada, on October 13-14, 1968.

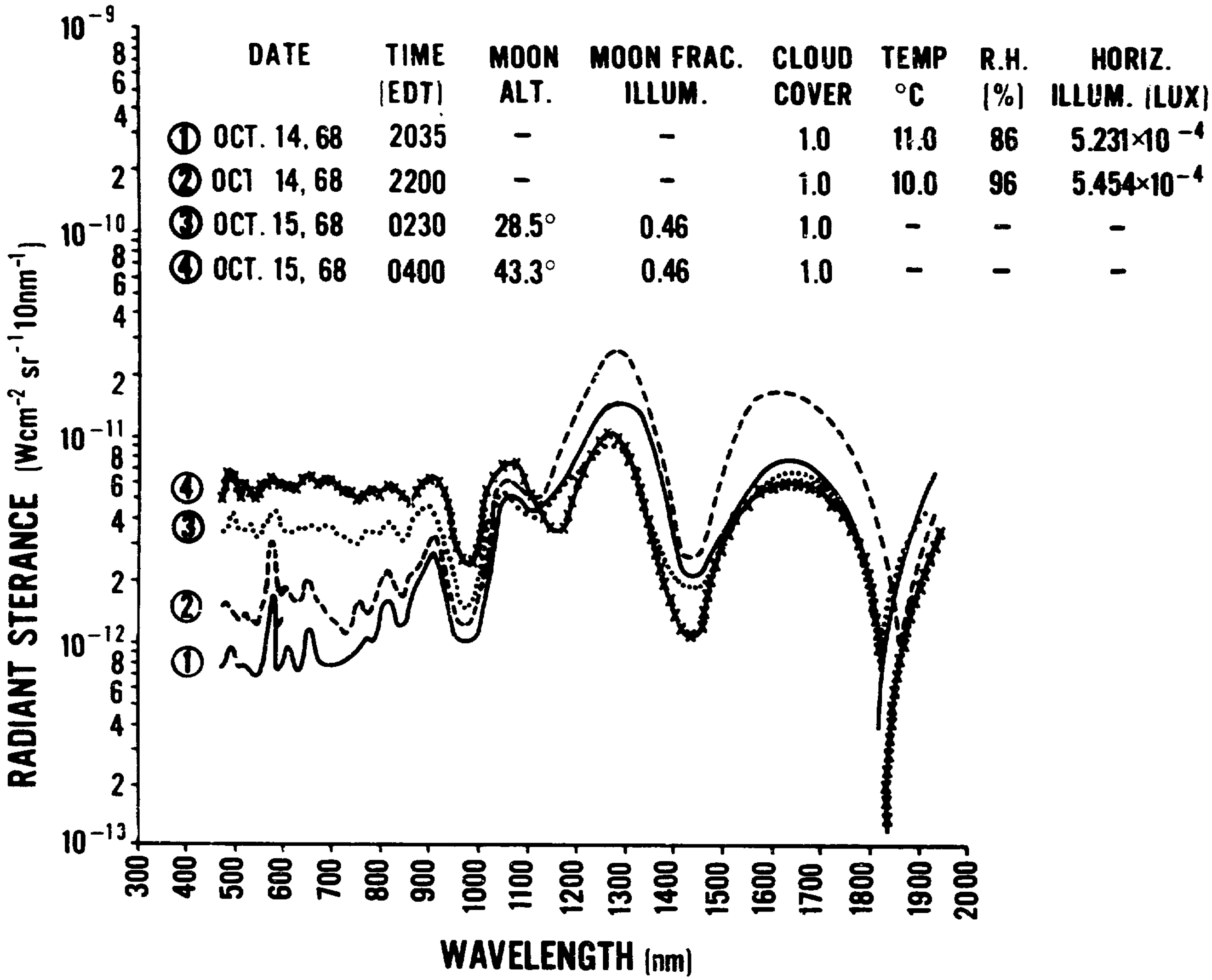

Fig. 13. Night-sky radiant sterance spectra recorded at Lake Montauban, Canada, on October 14-15, 1968.

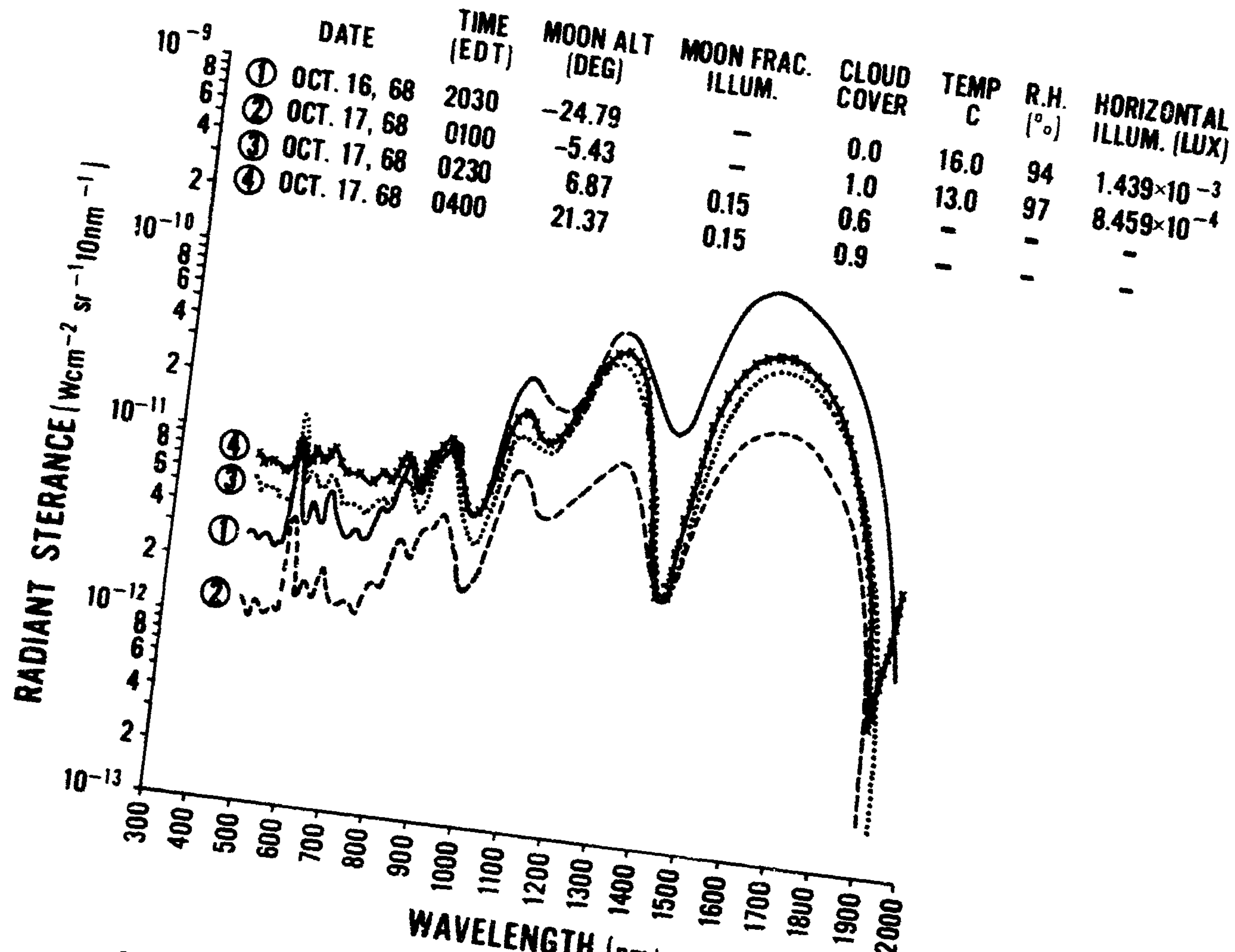

Fig. 14. Night-sky radiant sterance spectra recorded at Lake Montauban, Canada, on October 16-17, 1968.

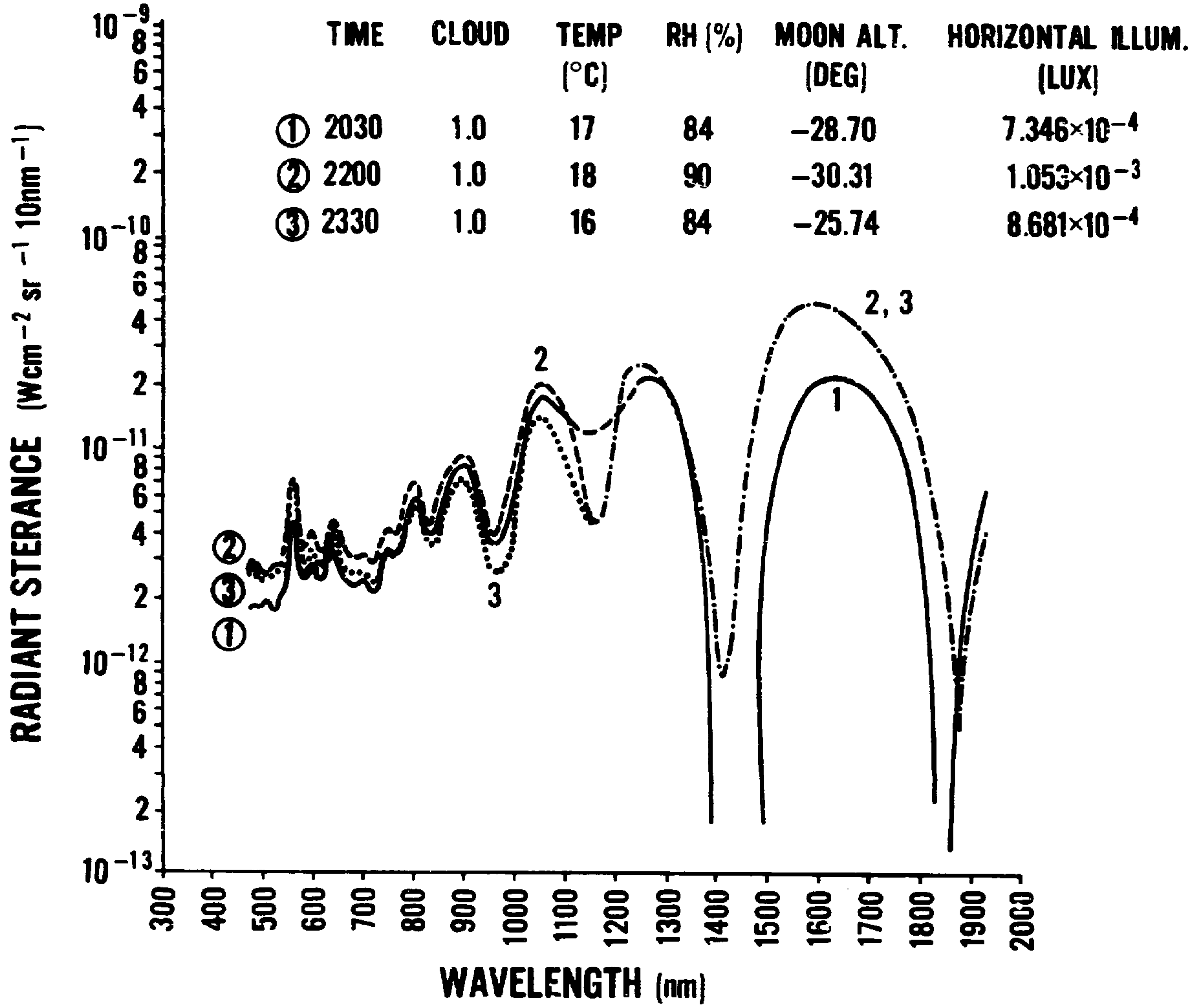

Fig. 15. Night-sky radiant sterance spectra recorded at Lake Montauban, Canada, on October 17, 1968.

VII. DISCUSSION OF SPECTRA

The general features of night-sky spectra are governed by the relative contributions of airglow, mainly due to atomic oxygen and hydroxyl emissions originating in the upper atmosphere, and moonlight as propagated through the earth's atmosphere. In the visible part of the spectrum, oxygen OI 5577 A and unresolved 6300 A and 6364 A and unresolved doublet lines Sodium Na 5896-5890 A dominate the night-sky spectrum until the solar radiation contribution due to lunar reflection becomes very large. Atmospheric attenuation is quite pronounced around 765, 850, 950, 1150, and 1380 nm mainly due to water vapor absorption. The slope of the lunar radiation spectrum in the visible region depends upon the altitude of the moon in the sky. When the moon is close to the zenith, the lunar radiation traverses one air mass of earth's atmosphere. At any other angle from the zenith, called the zenith distance, the radiation traverses longer paths through earth's atmosphere. Figure 16 shows solar spectral radiant incidance (irradiance) curves[24] with varying optical air masses. Night-sky radiation spectra under moonlight conditions with various lunar elevations indicate variations of slope similar to those in Fig. 16. The radiant sterance spectrum of a ground level white diffuse reflector illuminated by moonlight and night-sky contains a larger proportion of shorter wavelength radiation than that of the lunar radiation when observed directly. This blue enhancement is caused by the contribution of Rayleigh scattering of nightglow and lunar radiation by atmospheric molecules and atoms.

VIII. COMPARISON WITH OTHER MEASUREMENTS

One should be very careful in comparing radiation calculations or measurements made by various workers. There can be genuine and explainable differences in the measured results arising from the differences in the individual measuring procedures and the radiation measured. Our measurements represent ground-level observations of apparent night-sky radiant sterance averaged over the entire nominal celestial and atmospheric hemisphere which would contribute to radiant incidance on a horizontal surface on the ground at the time of measurement. No correction has been applied for atmospheric attenuation. Some investigators point their receivers up at particular regions of the sky involving selected sources of radiation and different amounts of atmospheric air masses. The spectral resolution of the individual measuring system and altitude of the site would also be reflected in the resultant spectra. Figure 17 shows a night-sky radiant sterance spectrum based upon the recent measurements made by Broadfoot and Kendall[25]

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[24] S. L. Valley, *USAFCRL Handbook of Geophysics and Space Environments,* 16-18 McGraw Hill Book Company, Inc. (1965).

[25] A. L. Broadfoot and K. R. Kendall, *Journal of Geophysical Research, Space Physics, 73,* 426 (1968).

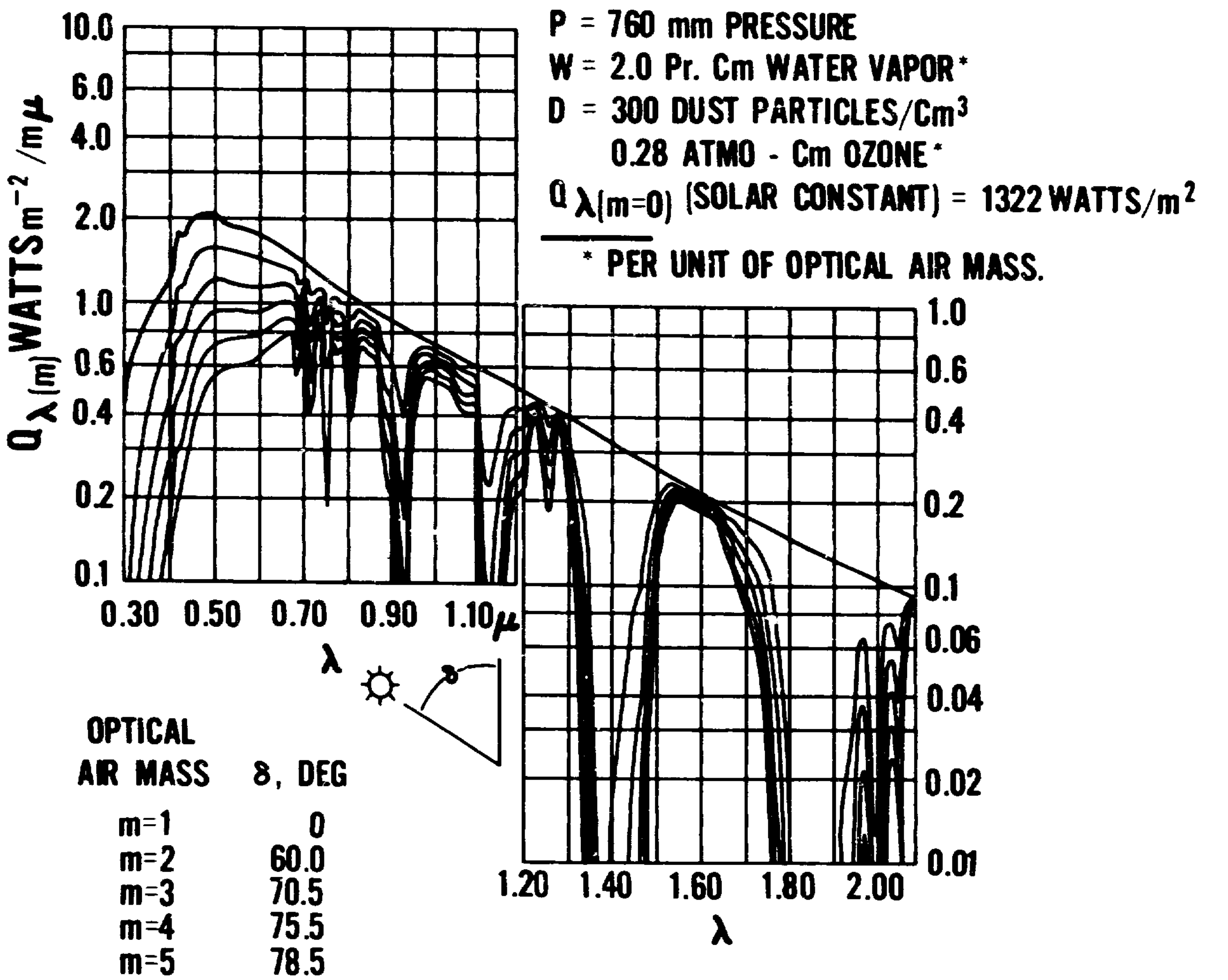

Fig. 16. Solar spectral radiant incidance (irradiance) curves at sea level with varying optical air masses (from Handbook of Geophysics, USAF, Air Research and Development Command, New York, 1961, Revised Edition).

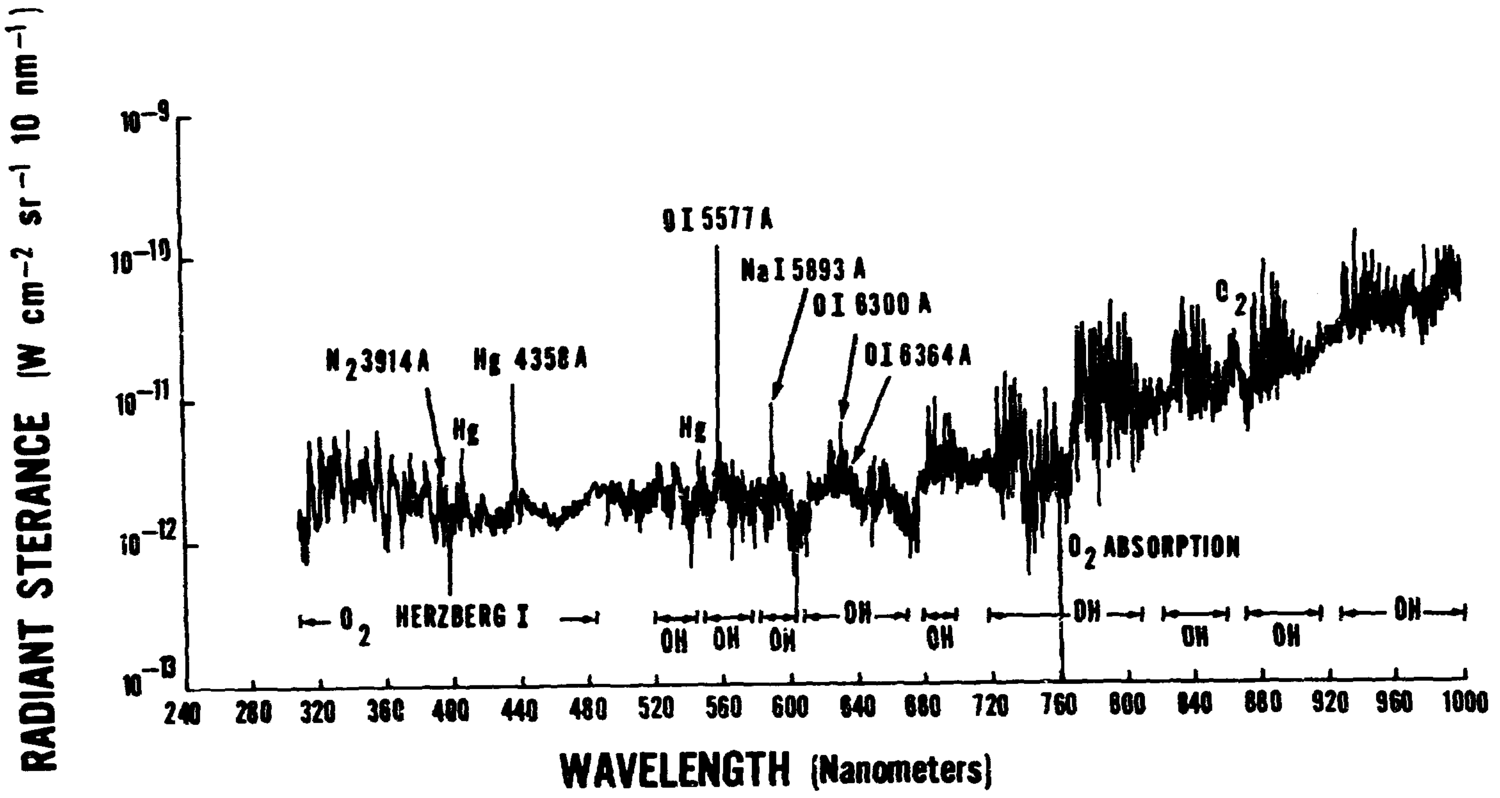

Fig. 17. Night-sky spectral radiant sterance at Kitt Peak Observatory as measured by Broadfoot and Kendall.

with a high-resolution (5 A) spectrograph at Kitt Peak Observatory at an altitude of 2080 meters. As expected, most of the atmospheric, water-vapor absorptions are missing in this spectrum. The prominent atmospheric airglow lines and bands are clearly resolved in the original publication. Figure 18 shows a recent, low-resolution, night-sky radiant sterance spectrum reported by Büchtemann and Höhn[26] recorded at ground level at Stephansried, a small village about 100 kilometers west-south-west of Munich, Germany. The spectrometer was pointed at the zenith sky. Pleiter and Morley[27] used a grating spectrometer to record ground-level spectral radiant incidance at Lake Montauban, Quebec, Canada. Figure 19 shows one of their radiant incidance (irradiance) spectra recorded just before moonrise at 2305 hours on 15 October 1968. In order to obtain the spectral radiant sterance of the sky, spectral radiant incidance should be divided by π steradians. Although the spectra reported by Büchtemann and Pleiter cover a smaller wavelength range compared to our spectra, in the region of overlap, viz 450 to 800 nm, the results are comparable to our measurements. In Fig. 20, we present average, night-sky radiant sterance for the given altitude and various moon phases for clear atmospheric conditions. One should use nighttime radiation spectra with care because the altitude and phase of the moon (fraction illuminated) as well as the orientation of the illuminated plane and spectral transmittance of the optical air mass are constantly changing variables which influence the magnitude and spectral composition of nighttime radiation. For a given altitude A and phase angle φ, the horizontal, sea-level, spectral radiant incidance E_λ is given by the relation

$$E_\lambda = L(\varphi)\, E_{o\lambda}\, [T_{1\lambda}]^{m-1} \tag{21}$$

where $L(\varphi)$ is the lunar luminance phase function, $E_{o\lambda}$ is the sea level horizontal, spectral radiant incidance when the full moon is at the zenith, $T_{1\lambda}$ is the vertical atmospheric spectral transmittance for a unit optical air mass, and m is the atmospheric air mass which is a function of the lunar altitude.[28]

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[26] W. Büchtemann and D. H. Höhn, *Spectral Radiance of the Sky and Terrestrial Irradiance in the Wavelength Range from 0.38 to 0.84 Micrometer*, Technical Report T/0203/92310/91375 Astronomical Institute of the University of Tubingen (1970).

[27] D. Pleiter and G. A. Morley, *Night Radiation Measurements, Lac Montauban, Quebec, October, 1968*, Technical Report DREV TN 1865/70, Defense Research Establishment Valcartier, Quebec, Canada (1970).

[28] M. L. Vatsia, *Atmospheric Optical Environment*, Technical Report ECOM-7023, U. S. Army Electronics Command, Night Vision Laboratory, Attention AMSEL-NVVI, Fort Belvoir, Virginia.

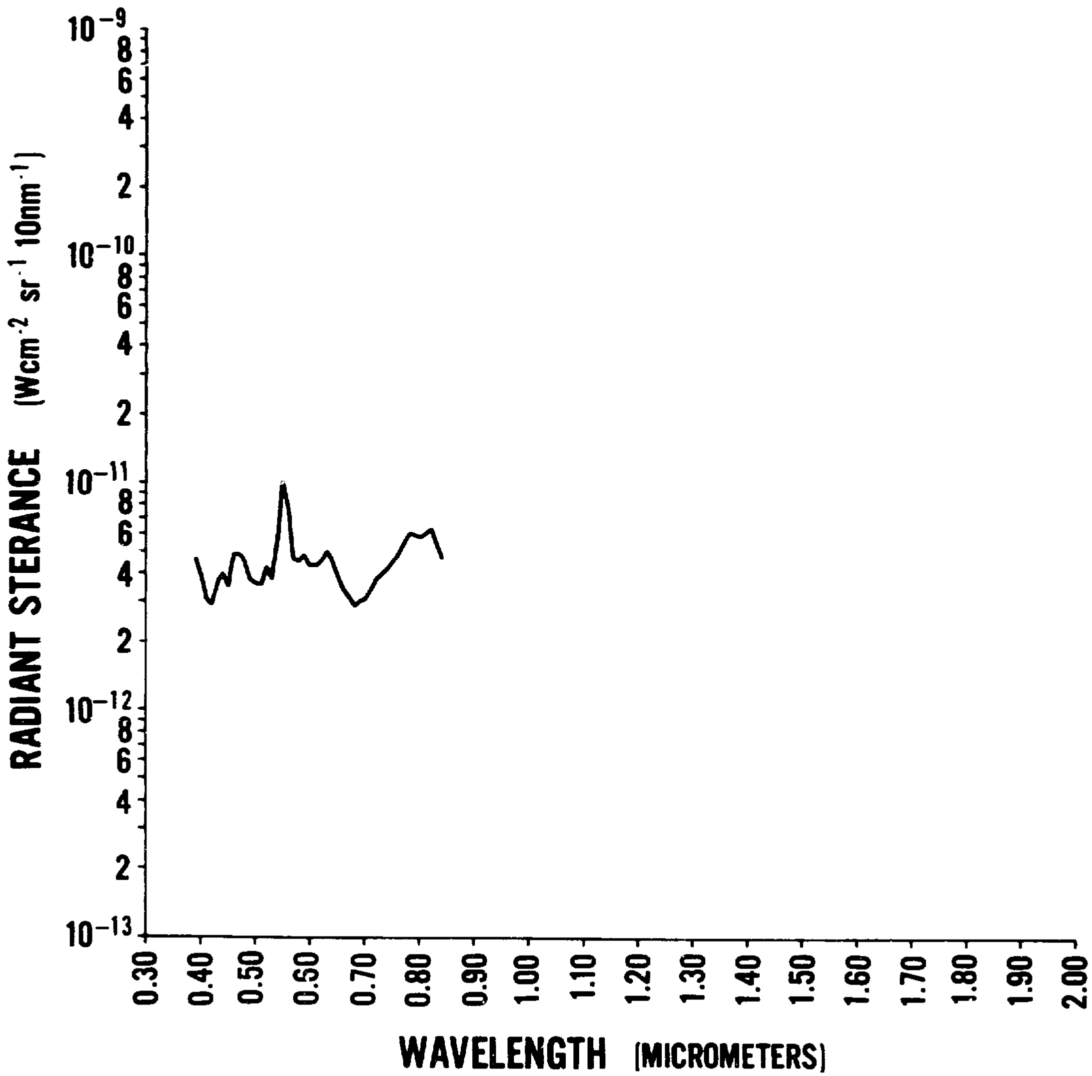

Fig. 18. Night-sky radiant sterance in Germany as measured by Büchtemann and Höhn.

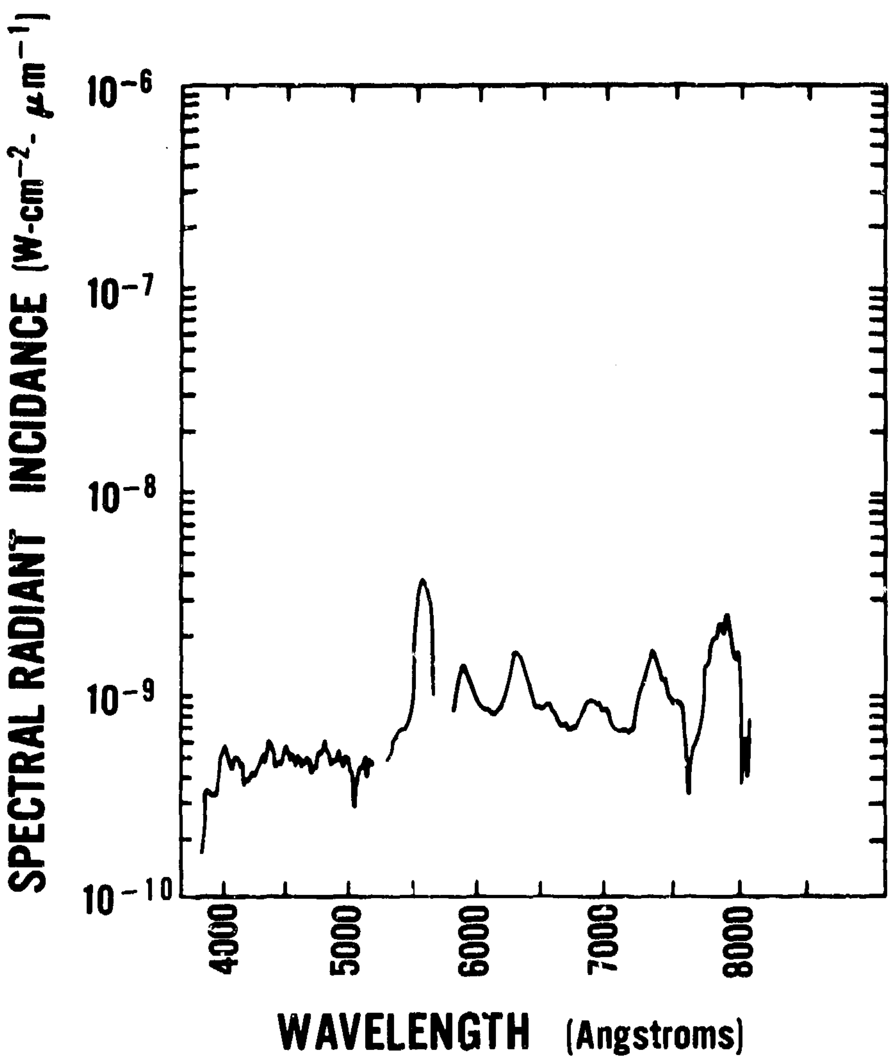

Fig. 19. Night-sky spectral radiant incidance on horizontal plane as measured by Pleiter and Morley.

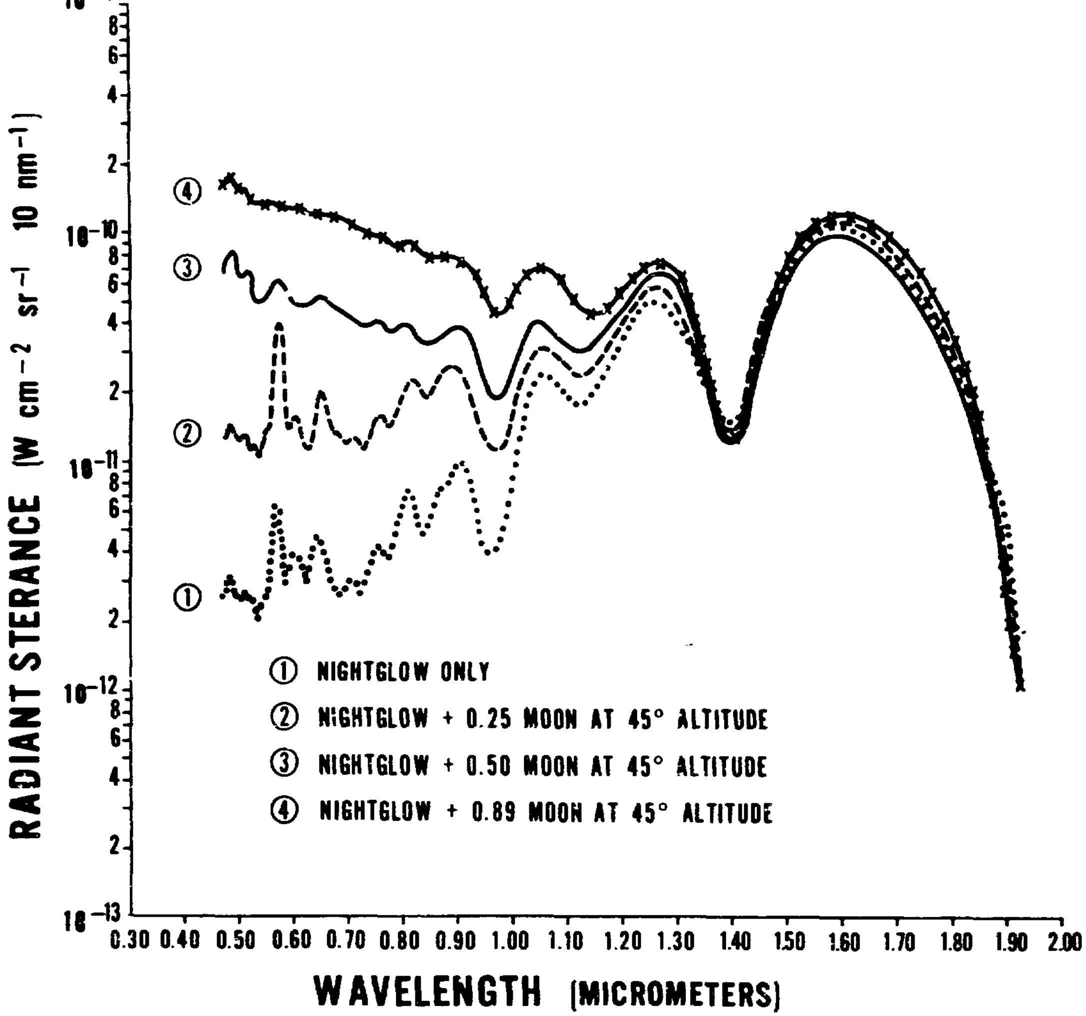

Fig. 20. Night-sky spectral radiant sterance for various phases of the moon.

IX. CONCLUSIONS

From the limited number of nonconjugate observations made in three widely separated geographical regions in the North American continent, the following conclusions are derived regarding the characteristics of the integrated, hemispherical, night-sky spectral radiance sterance as observed during the course of these measurements:

1. In the visible spectral range, from 450 nm to 700 nm, the average night-sky spectral radiant sterance varied from a minimum of about 4×10^{-12} W cm^{-2} $sterad^{-1}$ 10 nm^{-1} on a clear, moonless night to a maximum of about 4×10^{-10} W cm^{-2} $sterad^{-1}$ 10 nm^{-1} under clear, full-moon illumination conditions (Fig. 5).

2. In the near-infrared spectral region from 1000 nm to 1380 nm (in atmospheric windows II and III), night-sky radiant sterance varied from a minimum of about 2×10^{-11} W cm^{-2} $sterad^{-1}$ 10 nm^{-1} on a clear, moonless night to a maximum of about 1×10^{-10} W cm^{-2} $sterad^{-1}$ 10 nm^{-1} under clear full-moon illumination conditions (Fig. 5).

3. In the spectral region from 1400 nm to 1950 nm (atmospheric window IV), the night-sky spectral radiant sterance varied from a minimum of about 4×10^{-11} W cm^{-2} $sterad^{-1}$ 10 nm^{-1} on clear, moonless nighttime conditions to a maximum of about 1×10^{-10} W cm^{-2} $sterad^{-1}$ 10 nm^{-1} under clear, full-moon illumination conditions. In this spectral region, the lunar contribution to night-sky radiant sterance is relatively small (Fig. 5).

4. The variations in the magnitude of night-sky spectral radiant sterance due to variations in latitude were less pronounced than those produced by variations in meteorological conditions, especially the cloud cover and relative humidity (Figs. 7 and 12).

5. The largest fluctuations and variations in ground-level, spectral radiant incidance were produced by clouds. A thick and uniform cloud cover appeared to produce uniform attenuation over the entire spectral range of our observations. However, thin and scattered clouds with different configurations could produce selective spectral attenuation and even selective, spectral radiant sterance enhancement, especially in the visible spectral region depending upon the geometry and locations of the sources of radiation, the clouds, and the point of radiant incidance (Fig. 12, Curves 1 and 2).

6. To study the correlation of nighttime radiation with latitude, simultaneous conjugate measurements at different sites are necessary.

7. The user must exercise reasonable care in using lunar radiation data. The spectral-radiant incidance is a function of the angle of incidence of lunar radiation, the lunar fraction illuminated, and the variable spectral transmittance of the optical air mass.