Report of BAMIRAC

# SOME MEASUREMENTS OF SKY EMISSION IN THE 5-25-MICROMETER REGION

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October 1968

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INFRARED PHYSICS LABORATORY
Willow Run Laboratories
INSTITUTE OF SCIENCE AND TECHNOLOGY



Contract DAHC15 67 C 0062



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8418-1-R

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ACKNOWLEDGMENTS

Appreciation is expressed to Mr. David Anding who provided the band-model calculations, and to Mr. Frederick Smith for his considerable contributions in gathering and reducing the data.

ABSTRACT

An experimental study of the thermal radiation from the atmosphere is described, and some preliminary results are presented. These consist of moderately low-resolution spectra obtained with the instrument looking directly upward for various clear-sky weather conditions at Willow Run, Michigan. Comparisons are made with spectra representing band-model predictions based on standard atmospheric temperature and water vapor profiles adjusted to values measured at ground level. The agreement is satisfactory in the centers of the molecular bands; the uncertainties in the 10-12-$\mu$m continuum region are discussed.

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# SOME MEASUREMENTS OF SKY EMISSION IN THE 5-25-MICROMETER REGION

## 1
## INTRODUCTION

Knowledge of the magnitude of downwelling thermal radiation from the earth's atmosphere, hereafter referred to as sky emission, is required for a number of purposes ranging from meteorological and astronomical studies to the design of optical instruments for military applications. There is, of course, a vast amount of literature concerning the infrared spectral properties of the atmosphere and its constituent gases, much of which was obtained from direct measurements of atmospheric transmission. From such data one can calculate values expected for the sky emission using procedures varying from detailed line-by-line computations to approximations based on band-model representations. Much of this subject has been discussed by Goody [1]; the use of band-models for atmospheric transmission calculations was recently reviewed by Anding [2]. Such representations can easily be extended to handle emission as well as absorption [3].

The reliability of these calculations depends to a great extent on the knowledge of the temperature and composition profiles within the atmosphere. With exact information, obtained for a particular time and place by radiosonde probe or other means, the theory is sufficiently well developed, and the spectral parameters well enough known, that the calculations could be presumed to be dependable, at least in the centers of the stronger molecular bands. However, it would be very useful if such calculations could also be shown to be reasonably valid when based on standard temperature and composition profiles adjusted to local ground conditions.

Since only a few sets of spectral data were available [4-7] for comparison with calculated values, a series of experimental measurements of infrared spectral radiances were made at Willow Run for various clear-sky conditions. This report presents some preliminary results of that investigation.

## 2
## EXPERIMENTAL ARRANGEMENTS

For the initial phase of this investigation, attention was confined to low-resolution spectral radiance at zenith. Since both calculations [3] and experimental data [8] indicated very small changes in sky emission with angles close to zenith, a narrow field of view was not deemed necessary. Accordingly, the rather simple apparatus schematically illustrated in figure 1 was assembled for these preliminary measurements.

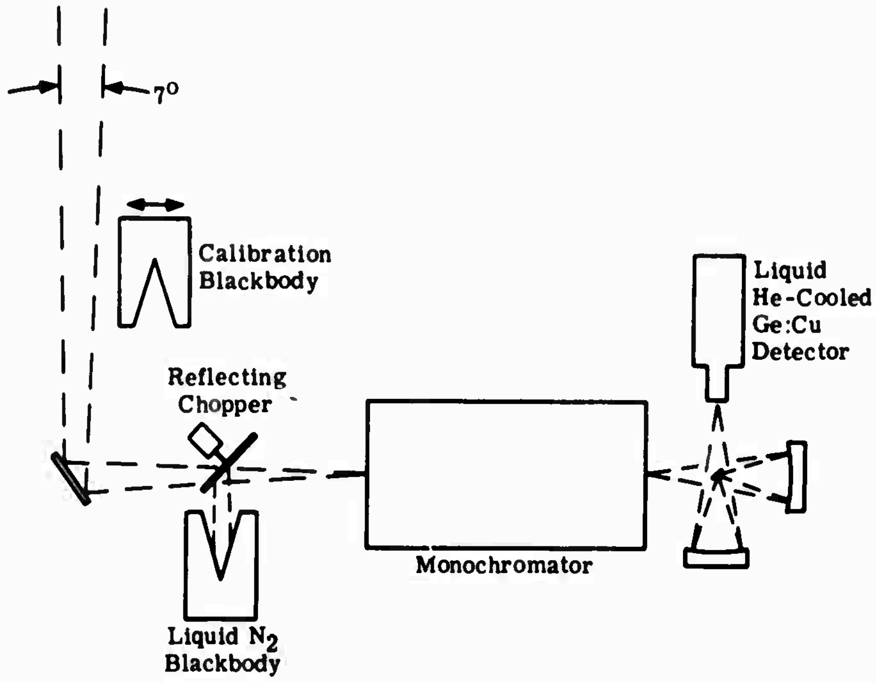


FIGURE 1. OPTICAL ARRANGEMENT FOR SKY EMISSION MEASUREMENTS

The principal component is the Leiss single-pass monochromator, for which NaCl, KBr, and KRS-5 prisms and a 75-line/mm gating blazed at 12 $\mu$m were on hand. The field of view of the instrument, defined by the internal optics of the monochromator, is approximately a 7° cone, alternately looking vertically upward and downward into a liquid nitrogen blackbody. The chopper and folding mirror were gold coated to minimize their emission. The detector is copper-doped germanium (cooled with liquid helium), the output of which was amplified, synchronously rectified, and recorded on a strip chart. The complete apparatus is shown in figure 2. Intensity calibrations were made by positioning another blackbody of appropriate temperature in the vertical beam; liquid nitrogen, dry ice, and ice point sources were assembled for this purpose. Wavelength calibrations were made by recording the absorption spectra of several gases in sample cells of appropriate length and pressure. Water vapor lines were used in the 5-8-$\mu$m and 17-25-$\mu$m regions, $NH_3$ from 8.5 to 13 $\mu$m, and $CO_2$ from 14 to 17 $\mu$m. With the grating installed in the monochromator, higher orders of the Hg green line provided the calibration points. Wavelengths for the molecular lines were obtained from references 9 and 10.

The data reduction proceeded as follows. Either immediately preceding or following a spectral scan of the sky, the nitrogen and dry ice or ice blackbodies would be positioned in the vertical beam and spectral scans for each obtained. The recording with the nitrogen blackbody in place would thus establish the zero level, and the other blackbody the intensity scale. Data were extracted from the calibration and the sky measurement chart recordings by means of a semi-automatic curve reader, the output of which was recorded on punched cards. A simple computer program then provided reduced data, also on punched cards, from which the final spectra were plotted automatically. The fidelity of the resultant curves in regard to spectral detail was primarily limited by the care paid by the operator of the curve reader in distinguishing weak spectral lines from electronic noise in the original recordings. In the present study, the emphasis was placed on the radiometric rather than the spectroscopic aspects of the data, so that perfectly faithful reduced spectra, which would have required considerably more time and expense using the curve reader to transcribe every wiggle, whether noise or signal, on the recorded spectra, were not particularly sought.

FIGURE 2. APPARATUS FOR SKY EMISSION MEASUREMENTS

Values of the barometric pressure and the relative humidity were obtained from the U. S. Weather Bureau station across the field at the Willow Run Airport facility; ground temperature measurements were obtained on the spot using a multiply shielded thermocouple probe.

## 3
## RESULTS AND COMPARISONS

A considerable number of spectra were obtained under atmospheric conditions ranging from strikingly clear winter days following passage of a cold front representing movement of dry cold Canadian air into Michigan, to nominally clear but quite hazy days characteristic of spring and summer warm spells. On several occasions spectra were obtained for skies clear except for faint and wispy patches of cirrus. The analysis of these is continuing; additional data are being gathered. The spectra in the 5-25-$\mu$m region are consistently similar in general appearance but differ considerably in absolute magnitudes of the radiances.

Typical of the spectra so obtained are those presented in figure 3 obtained using a salt prism as the dispersing element. The characteristic features of these spectra are readily identified. The 6.3-$\mu$m band of water vapor dominates up to about 8 $\mu$m, the 15-$\mu$m band of $CO_2$ from about 13.5 $\mu$ to wavelengths at which the pure rotational spectra of $H_2O$ become strong. The band centered about 9.6 $\mu$m is mostly due to ozone, largely concentrated at altitudes from 20 to 30 km.

Underlying these molecular bands is a continuum, most clearly evident in the 10-12-$\mu$ region, which arises from several sources. There are also a number of weak lines representing the extreme of the water rotational band, and several weak $CO_2$ bands. Figure 4 shows a spectrum of this region, obtained using the 75-line/mm grating, in which some of these features become evident. The identification of the water rotational lines was made by comparison with the higher resolution spectra obtained by Benedict et.al [11] in laboratory measurements of water vapor in a White cell. In addition to these lines, some of which are smeared out into an apparent continuum by insufficient resolution, there is underlying continuous radiation which has been attributed to two distinct sources: atmospheric aerosols and the sum of many very small contributions from the extreme wings of lines in neighboring and distant bands. The relatively small contribution of the line radiation compared with that of the continuum can be inferred from an examination of high-resolution solar spectra [12, 13].

Figure 3 shows the spectrum obtained for an exceptionally clear and cold day, and those for two clear days at more moderate temperatures. By virtue of the high optical densities of $H_2O$ and $CO_2$ in the 6.3- and 15-$\mu$m bands, the atmosphere radiates as a blackbody at the local ambient ground temperature near the band centers. In other spectral regions, at lesser optical densities, further penetration into the atmosphere obtains. Consequently, whereas the level of $H_2O$ and $CO_2$ radiation above the continuum fluctuates according to the ground ambient temperature, the 9.6-$\mu$m $O_3$ band, emanating primarily from the stratosphere, shows much less variation.

The value of radiances in these molecular bands are in good agreement with values predicted from appropriate band-model representations. Figure 5 shows an observed spectrum in comparison with a predicted spectrum provided by Anding [3]. The atmospheric temperature profile

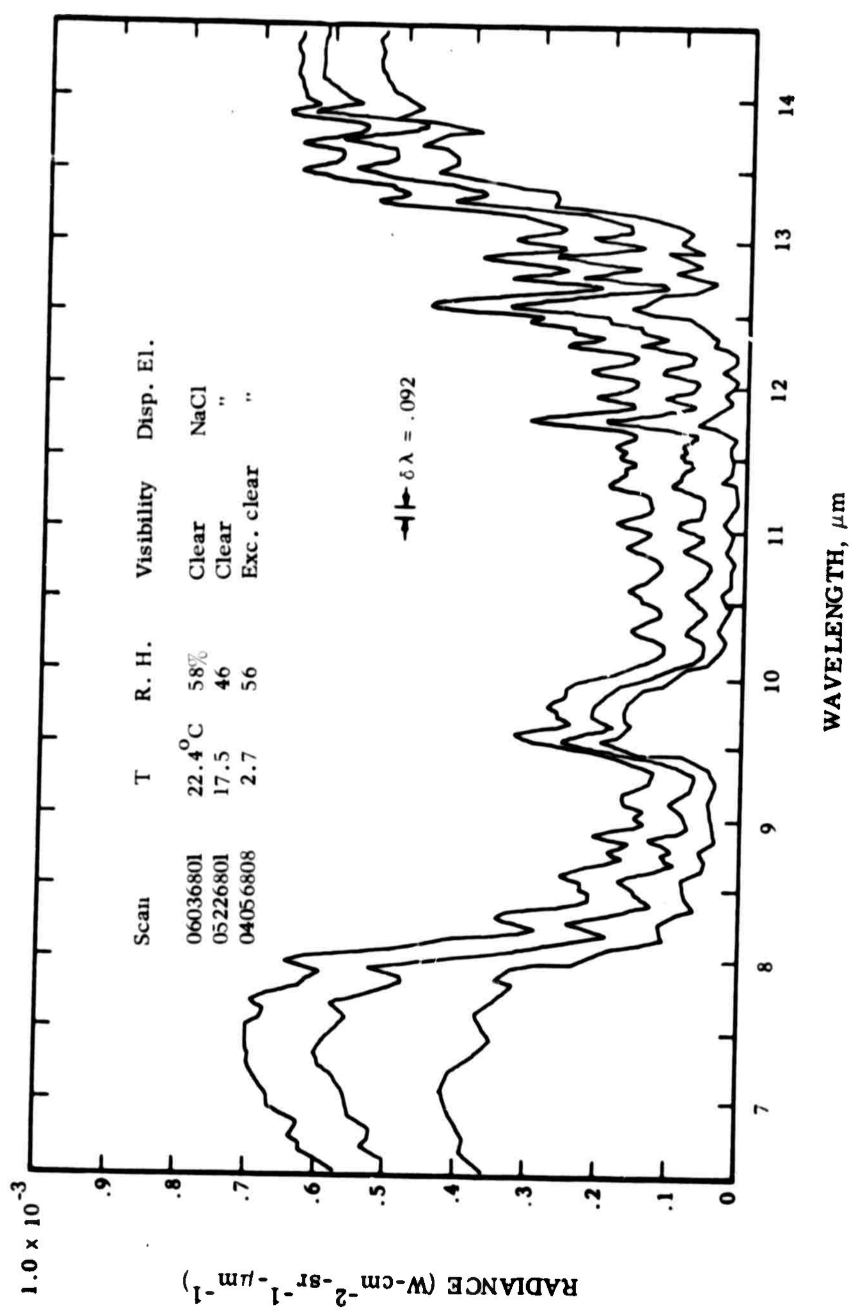


FIGURE 3. SKY EMISSION SPECTRA FOR SEVERAL CLOUDLESS-SKY CONDITIONS

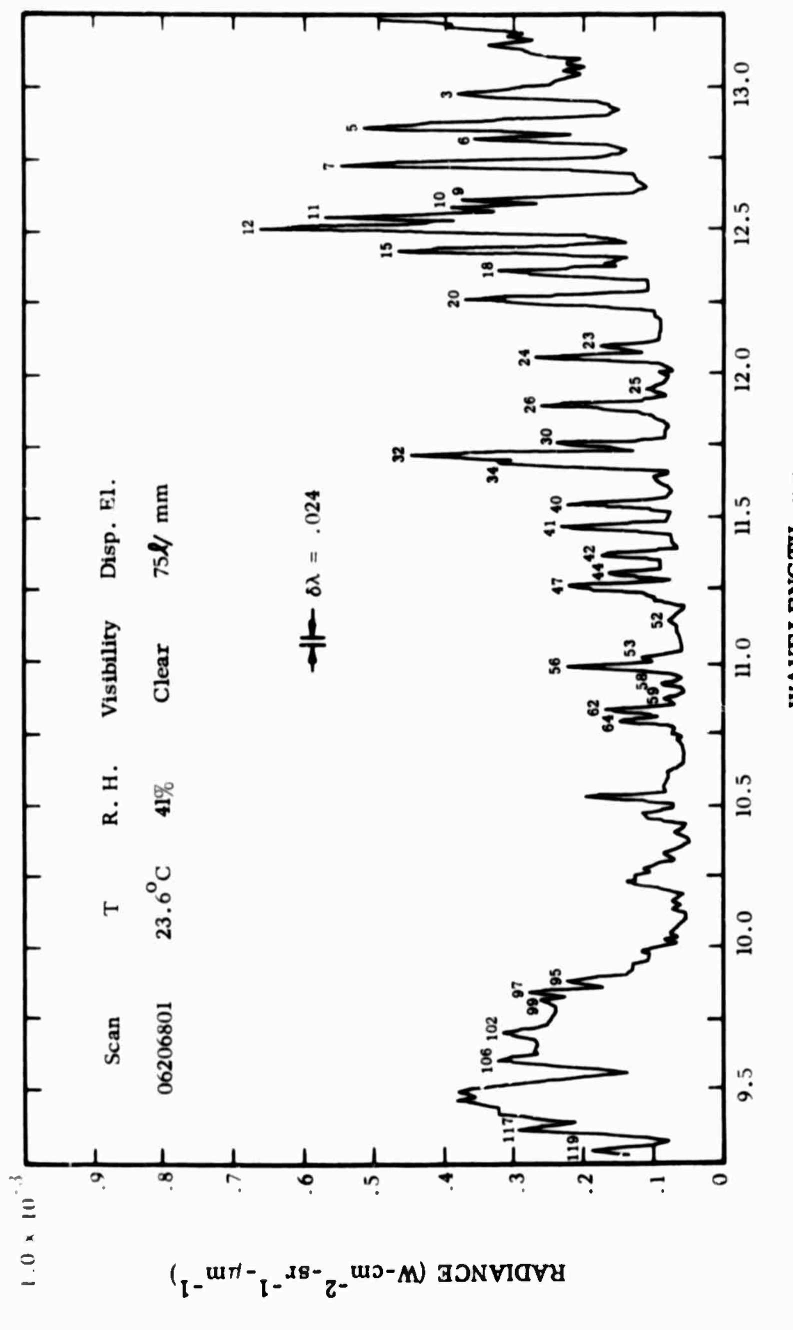


FIGURE 4. IDENTIFICATION OF $H_2O$ LINES IN SKY EMISSION SPECTRUM. Number designation from reference 11.

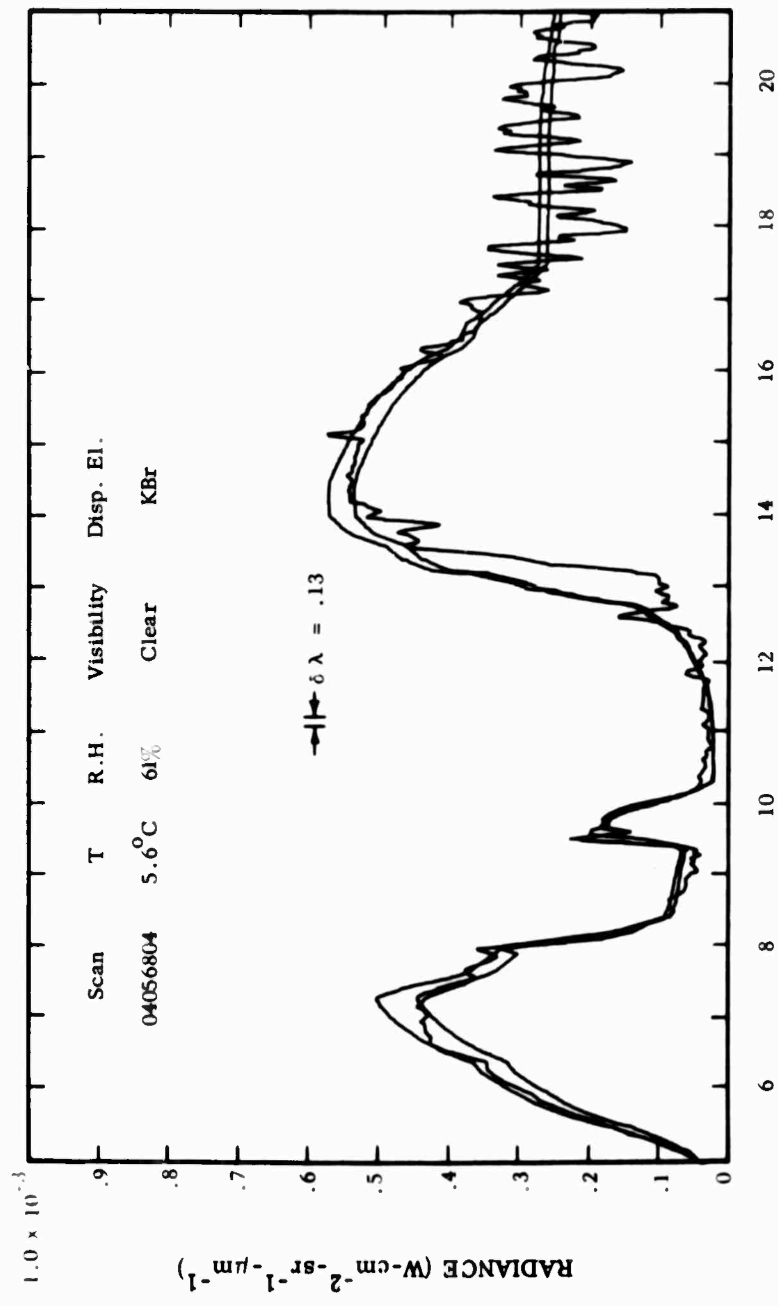


FIGURE 5. COMPARISON OF OBSERVED SPECTRUM WITH BAND-MODEL PREDICTION

was taken to be standard temperate [14] with the linear tropospheric variation adjusted to ground temperature; similarly the water vapor profile recommended by Gutnick [15] was adjusted for local ground-level humidity values. There was some question as to the proper value of ground temperature for use in the band-model calculation for two reasons. Frequently, there are steep gradients within a few feet of ground level, especially in the vicinity of buildings; the band-model calculation involves the approximation of an integral by a summation, so that the predicted values of radiance in optically dense regions of the spectrum becomes very sensitive to the incremental path length chosen. Accordingly, calculations were performed for measured ground temperature of $5^{o}C$ and the effective radiance temperature of $10^{o}C$ observed in center of the $H_2O$ and $CO_2$ bands. For the spectrum in figure 5, either fits the experimental data as well as the other. Comparable agreement was observed between other sets of data and calculations similarly performed. The disagreement along the short-wavelength slope of the 15-$\mu$m band reflects a poor evaluation of the band-model parameters from published transmittance data, which are being reexamined at this time.

The close agreement between the observations and predicted values in the 10-12-$\mu$m region in figure 5 is fortuitous; in other such calculations considerable disagreement was noted. For regions of continuum emission, of course, a band model per se is not required; rather, the standard equation of transfer, with suitable values for average spectral absorption coefficients, is appropriate. (This is equivalent, however, to the use of a "weak-line" band model based on the single parameter, the ratio of average line strength to spacing.) The discrepencies in such calculations reflect the uncertainty in the knowledge of the absorption coefficients for this region, and their dependence on the aerosol concentrations and distributions. To demonstrate the extent of such variations, radiative transfer calculations are being made using values of spectral absorption coefficients based on the measurements of Bignell [16], Bolle [5], and Yates and Taylor [17], and on the theoretical values given by Farmer [18]. Publication of the details of the calculation procedure and the results is planned.

The variation of emission in the 10-12-$\mu$m region is better illustrated in figure 6, in which spectra obtained with the grating are shown for several cloudless-sky conditions. The lower curve is indicative of an exceptionally clear, cold, dry day at Willow Run; the central curve a quite clear but warm day of average humidity, and the upper curve a comparably warm and humid but also quite hazy day. The two upper spectra indicate very clearly the contribution from atmospheric haze; in each case the water lines are comparable in magnitude, but the underlying continuum is considerably different.

The spectra in figure 6 are very similar in magnitude and detail to those recently reported by Bolle [5], Kondrat'ev [6], and Hanel [7]. The values of the spectral radiance of the continuum at 11.1 $\mu$m are shown in table I, in which Bell's [4] measurements are also included even

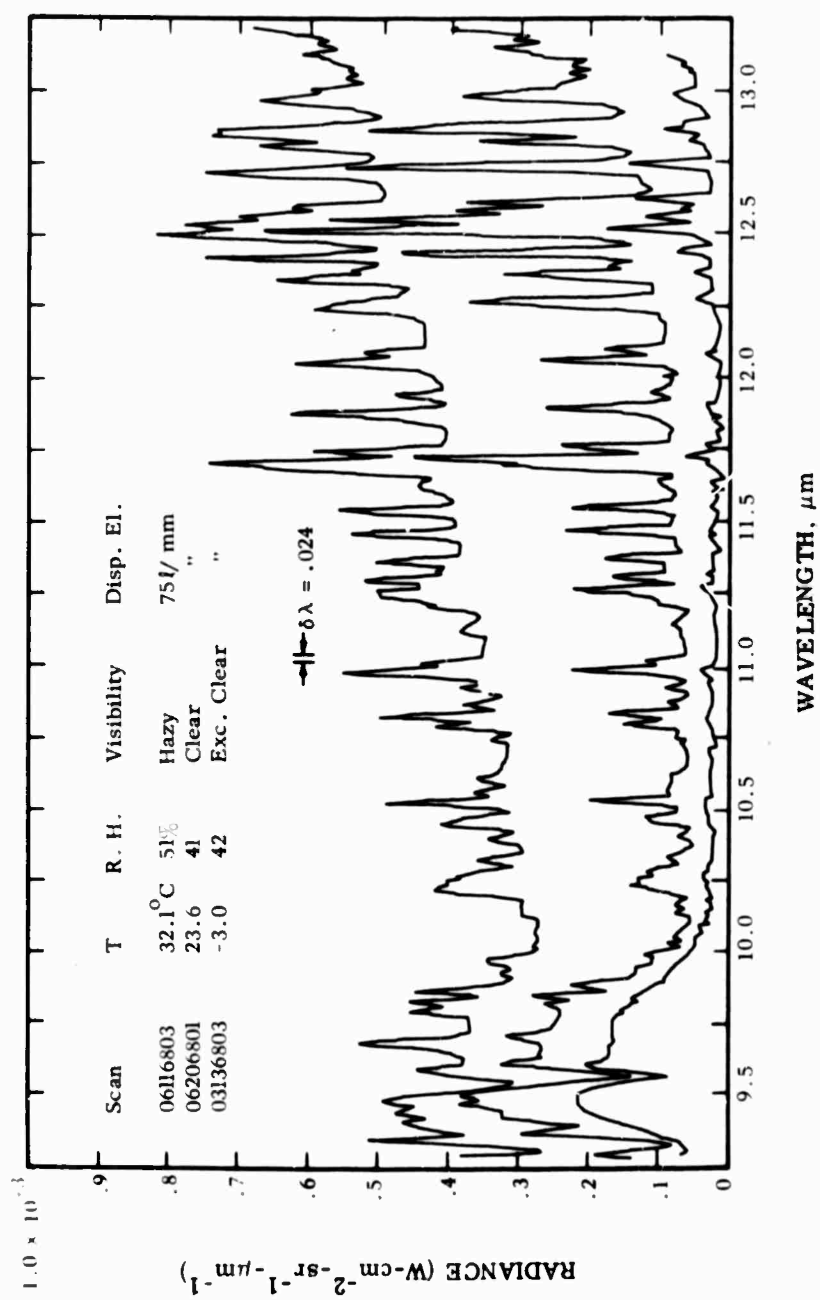


FIGURE 6. SKY EMISSION IN THE 10-12-μm REGION FOR SEVERAL CLOUDLESS-SKY CONDITIONS

though his considerably lower resolution undoubtedly yielded higher apparent values at this wavelength, because of unresolved lines in the region, than would have been observed at the approximately same higher resolution used by the other investigators. Note that the range of values observed in the present study well encompass the rest; however, the exceptionally clear sky data certainly must bear further scrutiny before conclusions are drawn regarding the minimum background levels at Willow Run and their interpretation in terms of molecular and aerosol emission.

TABLE I. SPECTRAL RADIANCES AT 11.1 μm FOR CLEAR SKIES AT ZENITH

| Investigator | Site | Range of Observed Radiances ($\mu W/cm^{-2}\text{-}sr^{-1}\text{-}\mu m^{-1}$) |
|---|---|---|
| Bell [4] | Pikes Peak, Colo. | 50-140 |
| Bolle [5] | Beer Sheva, Israel | 110-150 |
| Hanel [6] | Harvard, Mass. | 210 |
| Kondrat'ev [7] | Rostov-on-Don, USSR | 90 |
| Present study | Willow Run, Mich. | 20-350 |

## 4 CONCLUSION

The data presented herein are preliminary. Further refinements of the calibration and data reduction procedures are expected to lead to some modifications of the radiances, especially for the lower values in the 10-12-μm region. However, the spectra in their present state are sufficiently accurate to substantiate the use of standard atmosphere profiles, adjusted to local ground conditions, for band-model calculations of the prominent features of the infrared emission of the sky. These results also point up the need for more detailed studies of the 10-12-μm region to determine the relative values of molecular vs. aerosol contributions, to discriminate aerosol emission from scattered sunshine and earthshine, and to better characterize the nature of the molecular continuum. For such purposes, more complete data are required; these should include some higher resolution spectra, polarization data, observations of diurnal variations, measurements of visibility, determination of aerosol distributions by direct sampling or other means, scans with narrow fields of view from zenith to horizon, and data representative of a variety of geographic locales and climatic conditions. The continuing studies will be directed toward these objectives.

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**DOCUMENT CONTROL DATA - R & D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE

SOME MEASUREMENTS OF SKY EMISSION IN THE 5-25-MICROMETER REGION

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

C. B. Arnold and F. S. Simmons

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| October 1968 | vi + 17 | 17 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>DAHC15 67 C 0062<br>b. PROJECT NO.<br>ARPA Order No. 236, Amendment 26<br>c.<br>Program Code No. 7E40<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>8418-1-R<br>9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* |

10. DISTRIBUTION STATEMENT

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>Advanced Research Projects Agency, Department of Defense, Washington, D. C. |

13. ABSTRACT

An experimental study of the thermal radiation from the atmosphere is described, and some preliminary results are presented. These consist of moderately low-resolution spectra obtained with the instrument looking directly upward for various clear-sky weather conditions at Willow Run, Michigan. Comparison are made with spectra representing band-model predictions based on standard atmospheric temperature and water vapor profiles adjusted to values measured at ground level. The agreement is satisfactory in the centers of the molecular bands; the uncertainties in the 10-12-μm continuum region are discussed.

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Sky emission | | | | | | |
| Atmosphere | | | | | | |
| Thermal radiation | | | | | | |
| Band models | | | | | | |