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Infrared Absorption Program

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Project No. 4076

Task No. 407604
Work Unit No. 40760402

FINAL REPORT

Period Covered: Jan. 1, 1965 - Jan. 31, 1968

28 February 1968

This research was partially supported by the National Aeronautics and Space Administration

Contract Monitor
Robert W. Fenn
Optical Physics Laboratory

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INFRARED ABSORPTION PROGRAM

Final Report

Gilbert N. Plass

Abstract

A number of aspects of the interaction of radiation with planetary atmospheres have been studied. The variations to be expected in the transmission of radiation from thermal sources (continuous in wavelength), from flames (molecular bands), and from laser sources (essentially monochromatic) is derived. The scattering and absorption of Mie particles is studied because of the importance of aerosols in our atmosphere. Multiple scattering of light is important in any realistic model of the earth's atmosphere. A sophisticated Monte Carlo method has been developed to follow the path of a photon as it is scattered or absorbed by collision with atmospheric molecules, aerosols, and water droplets. Results have been derived from the Monte Carlo calculations for many different conditions. The radiant intensity, flux, and polarization are calculated at arbitrary levels in the atmosphere.

The scientific results obtained during the period of this contract have been described in detail in ten reports issued during the term of the contract and in twelve papers which have either been published or have been accepted for publication in scientific journals. It will be unnecessary to repeat the details of the work which is given in these papers. Instead the work is summarized and discussed in this final report.

In previous papers we have studied the transmission of infrared radiation through the atmosphere from thermal sources, i.e. the emitted energy is considered as continuously and uniformly emitted over the wavelength region of interest. During the present contract we have studied (P3) the transmission of laser radiation (i.e. essentially monochromatic radiation) along atmospheric paths. The absorption of laser radiation along slant paths is calculated first for the case when the absorbing gases are distributed uniformly throughout the atmosphere and when the temperature variation of the line intensities and half-width can be neglected. These results were then generalized to include cases of nonuniformly distributed gases with a temperature variation along the path. The effect of the overlapping of spectral lines is studied through the use of the Elsasser regular band model. From these results it is possible to predict the absorption along a slant path if the atmospheric parameters are known.

Flame radiation was also studied (P8) where the radiation is emitted by molecular bands. General expressions have been derived for the radiance of a nonisothermal gas in terms of the equivalent width of the relevant spectral lines. The equivalent width may be obtained from exact calculations which use molecular constants or from an appropriate expression from the theory of band models. The Curtis-Godson approximation may be used under certain conditions to simplify the calculations of the radiance. Illustrative calculations show how the radiance can be calculated for various temperature distributions within the flame.

The emission and scattering of radiation in the atmosphere and in flames depends to a considerable extent on the aerosols and other particles which scatter and absorb the radiation. Thus a considerable portion of this contract was spent in understanding better the analytic description of these events as given by the Mie theory. We have written an extremely efficient code which calculates the cross sections for scattering and absorption and the angular intensity of electromagnetic radiation interacting with spherical particles of complex index of refraction.

Aluminum oxide is an important constituent of flames and its optical properties are quite well known. Our Mie program was used (P1) to calculate the scattering and absorption cross sections for aluminum oxide over a temperature range from 1200°C to 2020°C. It was found that the efficiency factor for absorption increases by a factor of 40 at a wavelength of 2 microns as the temperature increases form 1200°C to 2020°C.

Another paper (P2) studied the Mie scattering and absorption efficiency factors as a function of the size parameter and of the absorbing power of the particle. Both the total efficiency factors and the scattered intensity as a function of angle were considered. The influence of the absorption on the sharp resonances which occur for the larger values of the size parameters was also considered.

Another paper (P4) discusses in detail the dependence of the Mie efficiency factors on the size parameter x and on n_1 and n_2 (the real and imaginary parts of the index of refraction). The efficiency factor for absorption is found to be proportional to n_2 over a considerable range of values which are specified. As n_2 increases, the efficiency factor for scattering in most cases first decreases to a minimum value and then passes through a maximum. The half-width of the angular intensity function is calculated over a range of values of n_1 and n_2. This half-width varies as x^{-1} when x is greater than unity and is relatively insensitive to the values of n_1 and n_2.

Still another paper on Mie scattering (P5) explored the effects of resonances on the efficiency factors. Among the interesting features discovered are the following: (1) the maximum value of the extinction efficiency factor at the first resonance decreases rapidly when a small amount of absorption is introduced; (2) over a considerable range of the parameters the width of the first resonance of the extinction efficiency factors is proportional to ${n_1}^{-4}$ when there is no absorption and to $n_2{n_1}^{-2}$ when there is absorption; (3) when $n_1 >> 1$, the scattered intensity near the first resonance is predominately forward, symmetrical, or predominately backward when x is respectively somewhat smaller than, equal to, or larger than the resonance value; (4) as n_2 increases, the forward scattered intensity first increases before it decreases for x greater than unity; (5) strong forward scattering occurs on one side of a resonance and strong backward scattering on the other side, although this effect may be obscured by other factors for high multipole resonances.

The above investigations of Mie scattering enable us to calculate the single scattering diagrams for any desired size distribution of particles and for any value of the index of refraction. Thus any aerosol distribution in the atmosphere can be described and its scattering properties calculated for use in atmospheric scattering calculations.

The most important result of the contract has been the development of a code which calculates the multiple scattering of light by Monte Carlo methods. Virtually any possible combination of factors in the atmosphere can be included in the calculation including molecular absorption and scattering, scattering and absorption by aerosols and water droplets, and reflection and absorption by any type of planetary surface. This work is described in detail in six published papers (P6,7,9,10,11,12).

In the first paper (P6) a single scattering function is used which is appropriate for cumulus clouds at 0.7μ wavelength. The protons are followed through a sufficient number of collisions and reflections from the lower surface (which may have any desired albedo) until they make a negligible contribution to the intensity. The cloud albedo and the mean optical path of the transmitted and reflected photons are given as a function of the solar zenith angle, optical thickness, and surface albedo. The numerous small angle scatterings of the photon in the direction of the incident beam are followed accurately and produce a greater penetration into the cloud than is obtained with a more isotropic and less realistic phase function.

In the second paper (P7) the reflected and transmitted radiance and flux of visible radiation is calculated for cumulus clouds of various thicknesses. The variation with solar zenith angle and the surface albedo is also given. When the surface albedo is zero, the reflected radiance has a relative maximum at the horizon (except for very thick clouds and incident beam near the zenith). When the incident beam is near the horizon, there is a strong maximum in the reflected radiance on the solar horizon and a pronounced minimum near the zenith. There is a strong maximum in the transmitted radiance around the direction of the incident beam until the cloud becomes thick in that direction.

In the third paper (P9) the influence of the absorption of the aerosols (single scattering albedo) is studied. When the single scattering albedo is small the reflected radiance approaches closely the value calculated from the single scattering phase function, since very few photons can survive more than one collision without being absorbed. As the absorption increases the transmitted radiance at the zenith becomes larger relative to the value near the horizon. At the same time the maximum of the transmitted radiance moves from the incident direction toward the zenith.

In the fourth paper (P10) the scattered and reflected light is calculated for clouds with various drop size distributions: isotropic; Rayleigh; haze continental; haze maritime; cumulus; nimbostratus. In general it is found that the reflected and transmitted radiances for the isotropic and Rayleigh models tend to be similar as are those for the various haze and cloud models. The reflected radiance is less for the haze and cloud models than for the isotropic and Rayleigh models, except for an angle of incidence near the horizon when it is larger around the incident beam direction. The transmitted radiance is always much larger for the haze and cloud models near the incident direction; at distant angles it is less for small and moderate optical thicknesses and greater for large optical thicknesses (all comparisons to isotropic and Rayleigh models).

In the fifth paper (P11) the technique is applied to a realistic model of the earth's atmosphere. The aerosol vs. height distributions proposed by Elterman and by Kondratiev et al are compared. The Rayleigh and aerosol scattering events are included in the calculation, as well as the ozone absorption, where appropriate. The results are given for wavelengths of 0.27, 0.3, 0.4, 0.7, and 1.67μ. The mean optical paths, the flux at the lower boundary, and the planetary albedo are also tabulated.

In the sixth paper (P12) the radiance and polarization of multiple scattered light is calculated from the Stoke's vectors. The exact scattering matrix for a typical haze and for a cloud whose spherical drops have an average radius of 12μ is calculated from the Mie theory.

The Stoke's vector is transformed in a collision by this scattering matrix and the rotation matrix. The two angles which define the photon direction after scattering are chosen by a random process which correctly simulates the actual distribution functions for both angles. The Monte Carlo results for Rayleigh scattering compare favorably with well known tabulated results. Curves are given of the reflected and transmitted radiances and polarizations for both the haze and cloud models and for several solar angles, optical thicknesses, and surface albedos. The dependence on these various parameters is discussed.

During the course of this contract considerable progress has been made in the development of the theoretical models which represent the absorption and transmission of radiation through planetary atmospheres. Satisfactory models were developed for the transmission of radiation from several different types of sources including continuous sources and monochromatic sources (lasers) as well as flame radiation. The development of a Monte Carlo code which takes account of the multiple scattering undergone by a photon enables one to study the influence of many different factors on the light field. More realistic models of the earth's surface is one of many items which can be included in Monte Carlo calculations. The ocean surface can be taken into account by actual calculation of the refracted and reflected path of the photon as it enters the ocean or is reflected from its surface. The great advantage of Monte Carlo methods is that problems of enormous complexity can be solved that cannot be dealt with by any other method. A full understanding of the scattering and absorption of light in the earth's atmosphere can be hastened by fully exploiting this technique.

REPORTS

R1. "The Temperature Dependence of the Mie Scattering and Absorption Cross Sections for Aluminum Oxide," April, 1965.

R2. "Mie Scattering and Absorption Cross Sections for Absorbing Particles," May, 1965.

R3. "The Absorption of Laser Radiation Along Atmospheric Slant Paths," July, 1965.

R4. "Electromagnetic Scattering from Absorbing Spheres," December, 1966.

R5. "Monte Carlo Calculations of Light Scattering from Clouds," May, 1967.

R6. "Radiation from Nonisothermal Gases," June, 1967.

R7. "Influence of Single Scattering Albedo on Reflected and Transmitted Light from Clouds," July, 1967.

R8. "Influence of Particle Size Distribution on Reflected and Transmitted Light from Clouds," August, 1967.

R9. "Calculations of Reflected and Transmitted Radiance for Earth's Atmosphere," September, 1967.

R10. "Radiance and Polarization of Multiple Scattered Light from Haze and Clouds," September, 1967.

PUBLICATIONS

P1. "The Temperature Dependence of the Mie Scattering and Absorption Cross Sections for Aluminum Oxide." Applied Optics, 4, 1616-1619 (1965).

P2. "Mie Scattering and Absorption Cross Sections for Absorbing Particles." Applied Optics, 5, 279-285 (1966).

P3. "The Absorption of Laser Raidation Along Atmospheric Slant Paths." Applied Optics, 5, 149-154 (1966).

P4. "Electromagnetic Scattering from Absorbing Spheres." Applied Optics 6, 1377-1382 (1967).

P5. "Resonance Scattering from Absorbing Spheres." Applied Optics 6, 1549-1554 (1967).

P6. "Monte Carlo Calculations of Light Scattering from Clouds." Applied Optics (March, 1968).

P7. "Radiant Intensity of Light Scattered from Clouds." Applied Optics (April, 1968).

P8. "Radiation from Nonisothermal Gases." Applied Optics 6, 1995 (1967).

P9. "Influence of Single Scattering Albedo on Reflected and Transmitted Light from Clouds." Applied Optics 7, 361-367 (1968).

P10. "Influence of Particle Size Distribution on Reflected and Transmitted Light from Clouds." Applied Optics (May, 1968).

P11. "Calculations of Reflected and Transmitted Radiance for Earth's Atmosphere." Applied Optics (June, 1968).

P12. "Radiance and Polarization of Multiple Scattered Light from Haze and Clouds." Applied Optics (July, 1968).

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