Technical Report

A Survey of Progress and Problems in the "Kaplan" Experiment

by

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PREFACE

A study of the literature on the "Kaplan" experiment for measurement of the thermal structure and water vapor concentration in the atmosphere has been begun. This report summarizes the results of this literature survey. Additional reports on this theoretical work will be published as additional progress is made.

A Survey of Progress and Problems in the "Kaplan" Experiment

Introduction

In 1959, Kaplan[1] suggested that measurement of the intensity of the outgoing infrared radiation of the earth and its atmosphere could provide a detailed analysis of the thermal structure and water vapor concentration in the atmosphere. These measurements would have to be made at carefully determined wavelengths and resolutions. The purpose of this short paper is to summarize the progress already made and to indicate what problems remain to be solved before useful results can be obtained.

Summary of Kaplan's Proposal

Kaplan's original paper contained an outline proposal for measurements and briefly indicated a method by which calculations could be made. The 15μ CO_2 band should be used to deduce the temperature structure, assuming that the CO_2 in the atmosphere is uniformly mixed. At the center of the band the radiation originates almost entirely from the top of the atmosphere, while in the far wings it comes from the ground level or the cloud tops. The intensity of the radiation is a function of the temperature at different altitudes, and by inverting the radiation equation the thermal structure can be deduced. The measurements must be made at high resolution, 5 cm^{-1} being proposed. Ten such measurements at roughly 10 cm^{-1} intervals would give the mean temperature in ten different layers of the atmosphere. The suggested method of calculation was a perturbation method, based on the departure from previously calculated standard atmospheric models.

Once the temperature structure is known, the results can be used to determine the moisture distribution from simultaneous measurements in the rotational or 6.3μ water vapor bands. The calculations can be made in a similar manner.

In addition, the surface temperature, or the temperature of the cloud tops of an overcast sky can be obtained from the 11μ atmospheric window. The 9.6μ ozone band would give information on the ozone distribution.

It is immediately apparent that a number of questions have to be answered before the experiment can be made. The more important of these fall under general headings as follows:

a. The calculation of the intensity of the outgoing radiation.

b. The inversion of the radiation equation.

c. A decision on the best frequencies and resolutions to make the measurements.

d. A consideration of the errors involved and an attempt to minimize them.

An attempt will now be made to show to what extent these problems have been considered. Most attention will be given to the 15μ CO_2 band, since the temperature distribution must be found before the water vapor concentration can be calculated. In addition the 15μ CO_2 band has a relatively simple structure.

a. Calculation of the intensity of the outgoing radiation.

The calculation of the intensity of the outgoing radiation has received much consideration in the literature, since it is very closely associated with the heat balance of the earth. The accuracy with which the intensity can be found is clearly a limiting factor affecting the whole experiment. It is therefore of the greatest importance that this quantity be found as precisely as possible. The chief obstacle is the determination of the atmospheric transmission, a function of temperature, and pressure, and a very sensitive function of wavelength.

Each absorption band is composed of many individual lines of differing intensities and widths. The broadening of these lines is due mainly to collisions of the absorbing molecules with other molecules in the atmosphere. In this case, a single line has the Lorentz shape, given by:

$$k(\nu) = \frac{S}{\pi} \quad \frac{\alpha}{(\nu - \nu_o)^2 + \alpha^2} \qquad (1)$$

where

$k(\nu)$ = absorption coefficient at frequency ν

S = total line intensity

α = half width of the line

ν_o = frequency of the line center

This shape agrees well with experimental results, except in the far wings where the absorption drops off more sharply than predicted.

At very high altitudes where the atmosphere is rare, collision broadening becomes less important and Doppler broadening predominates. This broadening occurs as a result of the motion of absorbing molecules. Since the absorption is low under these conditions, little error will result in considering Lorentz broadening only.

The total line intensity S is a function of temperature only. A strong line exhibits a slight decrease in intensity with increasing temperature, whereas a weak line increases considerably. This dependence may fairly readily be calculated. [2, 3]

The half width α is a function of temperature and pressure. The dependence is given by

$$\alpha = \frac{F}{2\pi}$$

$$= \alpha_o \frac{P}{P_o} \sqrt{\frac{T}{T_o}} \qquad (2)$$

where

F is collision frequency

T is the absolute temperature

P is the pressure

α_o is half width at temperature T_o and pressure P_o.

A correction to this formula[4] can be made by replacing P by

$$P_e = P + (B - 1)p \qquad (3)$$

where

P_e is called the equivalent pressure

B is the self broadening coefficient

p is the partial pressure of the absorbing gas.

In the case of CO_2, where the proportion of absorbing gas is assumed constant, equation (2) will still hold. However, it should be taken into account in the water vapor bands.

Because each absorption band contains so many lines, it is impractical to calculate the absorption coefficient, even for a narrow portion of the band, by the contribution from each single line. To overcome this

difficulty, a number of different models for absorption have been proposed, each of which tries to simulate the actual shape and intensity and distribution of the lines.

The Elsasser Band[5] is assumed to consist of an infinite number of spectral lines, each with the same intensity and half width, and equally spaced.

The Statistical Model[6] supposes that the positions of lines occur at random and that the intensities can be represented by a probability distribution.

The Random Elsasser Model[7] is composed of several groups of lines, each of which forms an Elsasser band, superposed to give a nearly random spacing.

The problem with these models is that none of them corresponds very closely to the actual structure of the absorption bands and consequently lead to errors. In addition, the absorption due to the wings of lines in adjacent frequency intervals are not taken into account; the wings of lines have a great influence on the radiation intensity.

Plass et al[8] have recently (1962) introduced a Quasi-Random Model, which has done much to overcome these difficulties. Transmission tables for CO_2 and water vapor over a wide range of frequency, temperature, pressure and path length using this model are now available.

For a comprehensive survey of band models see Plass[7].

We shall now assume that the transmission has been accurately determined. With a given temperature and pressure structure for the atmosphere, and in the case of water vapor a given density distribution, the intensity of outgoing radiation as seen from a satellite may be calculated. The basic radiation transfer equation in a narrow interval centered at frequency ν, is given by:

$$I_\nu = \int_{p=o}^{p_s} B_\nu(T) \frac{d\tau_\nu(p)}{dp} dp + I'_\nu \mathcal{E}_\nu$$

where

I_ν is the intensity of the vertically upward radiation

$\tau_\nu(p)$ is the transmission of the atmosphere at pressure p and frequency

B_ν is the Planck function for that interval.

p_s is the surface pressure.

I'_ν is the intensity of radiation of the surface of the earth.

$\mathfrak{E}_\nu$ is the total transmission of the whole atmosphere at frequency ν .

b. The inversion of the radiation equation

Assuming that the outgoing radiation intensity has been accurately computed, the equation must be inverted to obtain the atmospheric structure.

Kaplan[9] uses a perturbation method. The atmosphere is stratified by 7 isobaric surfaces and the outgoing radiation intensity in 7 frequency intervals in the 15μ CO_2 band is calculated for a number of model temperature distributions. The model which best fits the observed radiation is found by the method of least squares. A more accurate solution is obtained by a perturbation technique, neglecting terms of order three or higher.

The results of a number of test calculations are given. In a few cases the process failed to yield convergent solutions. When a systematic error of 3% was added, the maximum error in temperature did not exceed about 6°C in any layer.

However, the addition of random noise made the errors much worse, and these were of an oscillatory nature. Details were not given in the paper.

Because of the difficulties caused by clouds in the atmosphere, Wark[3] considers only three frequency interval measurements confined to the central part of the 15μ CO_2 band, where radiation originates almost entirely from the cloud-free stratosphere. Integrating the radiation equation by parts and changing the variable from p to log p, the intensity of the outgoing radiation is used to compute the temperature at the "top of the atmosphere" and the lapse rate in two layers of the stratosphere.

The approach used by Yamamoto[10] differs slightly. Only the stratosphere is considered, with 4 frequency measurements, and polynomial approximations are used for the Planck function. Three methods are given:

1. Approximating the Planck function by polynomials and using numerical values for the transmission function.
2. Approximating the Planck function by polynomials and using Legendre polynomials to approximate the transmission function.
3. Using Chebyshev polynomials instead of Legendre polynomials.

These methods give a continuous temperature profile.

It should be noted that although the methods described by Wark and Yamamoto were illustrated for the stratosphere, they are applicable to the whole atmosphere, if the cloud distribution is known.

Unfortunately their methods are difficult to compare, partly because of the different number of measurements taken, and partly due to the different ways of expressing the results. It has become increasingly apparent that any method of inversion must be capable of modification to limit the oscillation in the solutions due to errors, both in measurement and calculation. One such way is to place a smoothness constraint on the solution. However, care must be taken not to lose too much information by its application.

c. The frequencies and resolutions of the measurements

Assuming that a method of calculating the intensity of the outgoing radiation is known, it is possible to consider the best frequencies and resolutions to make the measurements. In order to get the optimum results we should like small changes in temperature (or water vapor concentration) to produce large changes in intensity of radiation, especially if the noise level of the instrument is high. It would be useful to know how much more information could be obtained with a resolution of, say, 1 cm^{-1} compared with 5 cm^{-1} or 10 cm^{-1}, particularly when allowance is made for the fact that a smaller amount of radiation could not be measured to the same degree of accuracy, and that a longer time interval would be required for measurements.

Thus, we must distinguish between theoretical requirements which may be used to develop future instruments, and the most efficient way to use currently available instruments. The spectrometer now being developed by the Barnes Engineering Company[11, 12], has a resolution of 5 cm^{-1}, with six channels in the 15μ CO_2 band and one in the atmospheric window at 11.1μ . When this is flown from a balloon, the radiation equation will have to be modified to allow for the fact that measurements will be taken within the earth's atmosphere, the contribution from above the balloon being significant.

d. Errors

There are many different ways in which errors can be introduced. The more predominant of these can be classified under the following general headings:

1. Errors in measurement and calibration of the instrument. It is not within the scope of this paper to consider the nature of these errors, or how they can be minimized by suitable design, but it is important to know their magnitude, to estimate the accuracy of the final results. In addition this will give some indication of the accuracy with which the calculations must be carried out, and the reliability of the solution.

2. Errors in calculating the outgoing radiation. As previously indicated, the transmission is the chief source of errors. These errors can arise because of inaccuracies in the following values:

a. line strength
b. half width
c. line shape
d. the pressure/temperature dependence of these three quantities
e. inaccurate model of band absorption
f. the CO_2 concentration, or the temperature distribution in the water vapor band
g. overlapping from other bands

There may also be errors in numerical integration of the radiation equation. The use of a computer will be necessary to perform this calculation.

3. Errors in inverting the radiation equation and expressing the results. These errors are difficult to estimate. A fuller discussion has already been given in section b. Work on these lines is at present underway at the U. S. Weather Bureau in Washington, D. C. and will shortly begin at the University of Michigan.

From previous atmospheric soundings, the temperature at 25 mb is known to an accuracy of about two or three degrees Centigrade, at least over Continental North America and Europe. This will allow a good check of accuracy to be made in the CO_2 band. Information on the water vapor concentration in the atmosphere is quite sparse and it will be rather more difficult to evaluate the degree of error in these measurements.

Conclusion

There can be no doubt that the experiment proposed by Kaplan is feasible, with a great potential for procuring information on a global scale. However, the usefulness will depend on how carefully the measurements are made and on the accuracy with which they are interpreted.

In previous calculations it has been general to make assumptions which are not justified by physical reality. It is particularly important to determine the errors induced by these assumptions and to make corrected calculations where necessary.

Because of the complexity of the mathematical equations involved, it will be necessary to make many approximations. Every effort must be made to minimize the magnitude of these approximations and to estimate their effect on the final solution.

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