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USE OF SKYLAB EREP DATA IN A SEA SURFACE TEMPERATURE EXPERIMENT

First Quarterly Report

Prepared by
David C. Anding
Science Applications, Incorporated
Ann Arbor, Michigan 48103

For
National Aeronautics and Space Administration
Manned Spacecraft Center
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FOREWORD

The research described herein, which was conducted by JRB Associates - a wholly owned subsidiary of Science Applications, Incorporated, was performed under NASA Contract NAS9-13277. This first quarterly report covers the period from 17 February 1973 to 17 May 1973.

ABSTRACT

This report discusses an experiment to be performed on each of the three manned Skylab missions, the results of which will assess the ability of spaceborne infrared multispectral sensing to function as a means of providing improved estimates of sea surface temperature over that obtainable with a single channel radiometric instrument. The overall investigative program is outlined, the effort performed during the prelaunch phase is detailed, and pertinent results are presented.

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1.0 INTRODUCTION

A knowledge of the distribution of water surface temperature over all bodies of water on the earth's surface is of significant importance to a number of scientific communities. Such information would be particularly useful in locating various species of fish, in spatially mapping ocean and lake currents, and in estimating the exchange of thermal energy between the water surface and the atmosphere. In general, the more precise is the knowledge of the temperature distribution, the more useful are the data. However, the greater is the precision desired, the higher is the cost of achieving that objective. After consultation with those researchers who would be the eventual users of such data, the general concensus is that sea temperature accuracies of $\pm$ 1 K at a spatial resolution of approximately 1 km would be satisfactory. However, researchers associated with certain oceanographic applications desire even greater accuracies. A general requirement of the scientific community is that the time period between the collection of the data and its dissemination in a useful form be of the order of days. In essence, an accurate near real time synoptic view of the earth's water is desired.

Although such an objective could be satisfied in a number of ways, a feasible approach would be to utilize a spatially scanning space-borne system which includes a computerized data-reduction technique to facilitate rapid conversion of the measured data into a usable form, such as water surface temperature maps. Fortunately, most of the knowledge required to design such a system is presently available from the results of past analysis and measurement programs. In particular, spatially scanning space-borne systems have been flown, such as the ITOS I medium-resolution infrared radiometer, which provides the information required to estimate the sea temperature on a global basis. Smith, Rao, Koffler, and Curtis [1] of the National Environmental Satellite Center have developed a procedure which optimally converts the measured data into sea temperature maps. Unfortunately, the results do not meet the requirements of the scientific community, in regard to either absolute accuracy or spatial resolution, simply because the information obtained by a measurement of the radiance in a single spectral channel is insufficient to compensate accurately for the effects of atmosphere on the observed radiance. It has been postulated, however, that by measuring the radiance in more than one spectral region, improved estimates of the sea temperature at high spatial resolution are obtainable.

In particular, theoretical investigations have been performed [2, 3] to determine the extent to which multispectral sensing can be used to obtain improved estimates of sea surface temperature from space over those obtainable with a single channel radiometer. The investigations involved the use of radiative transfer models which reportedly gave results that were accurate representations of reality. The results were very encouraging in that two spectral channels gave estimates of sea surface temperature considerably more accurate than those obtainable with a single channel instrument. Although encouraging, the results remain tentative until they can be verified by experiment. The Skylab mission provides the first opportunity for a verification experiment.

The experiment described herein will utilize S191 spectrometer data acquired during each of the three Skylab missions to: (1) validate the radiative transfer models used in the initial investigations, (2) make direct measurements of the sea surface temperature through the application of multichannel temperature estimating algorithms developed from the radiative transfer models, and (3) generally assess the ability of spaceborne infrared multispectral sensing to function as a means of providing improved estimates of sea surface temperature. In addition, the experiment will provide inputs for defining the specifications for future sea temperature measurement systems.

The investigation will be performed in three phases; a prelaunch phase, a preliminary analysis phase, and a post-launch phase. A detailed account of the efforts to be performed during each phase is given in the experiment milestone plan [4]. Briefly, the prelaunch phase involved the refinement of previously developed radiative transfer models and algorithms and the development of software required for the overall investigation. During the second phase, S191 data obtained over cloud-free and stratus cloud-filled fields of view during each of the three Skylab missions, along with supporting air and surface data, will undergo a brief analysis, and if required, the S191, air, and surface data requirements will be modified for subsequent missions. The final phase of the investigation will involve a comprehensive analysis of all data acquired and a delineation of the potential of infrared multispectral sensing from space to function as a means of accurately measuring the sea surface temperature.

This first quarterly report presents an account of the effort performed during the prelaunch phase of the investigation and includes pertinent results.

2.0 PRELAUNCH INVESTIGATION

Since the Skylab sea temperature experiment was initially configured the state-of-the-art of performing atmospheric radiative transfer calculations has improved significantly. This is particularly true in the spectral region of concern, i.e., 7-14 μm. More recent calculations have demonstrated that previously used radiative transfer models were in error, implying that the previously derived temperature estimating algorithms must be revised. The effort required to accomplish this task involved first modifying the present radiative transfer model so that it produced results that compared satisfactorily with accepted values, and then revising the temperature estimating algorithms using the new model.

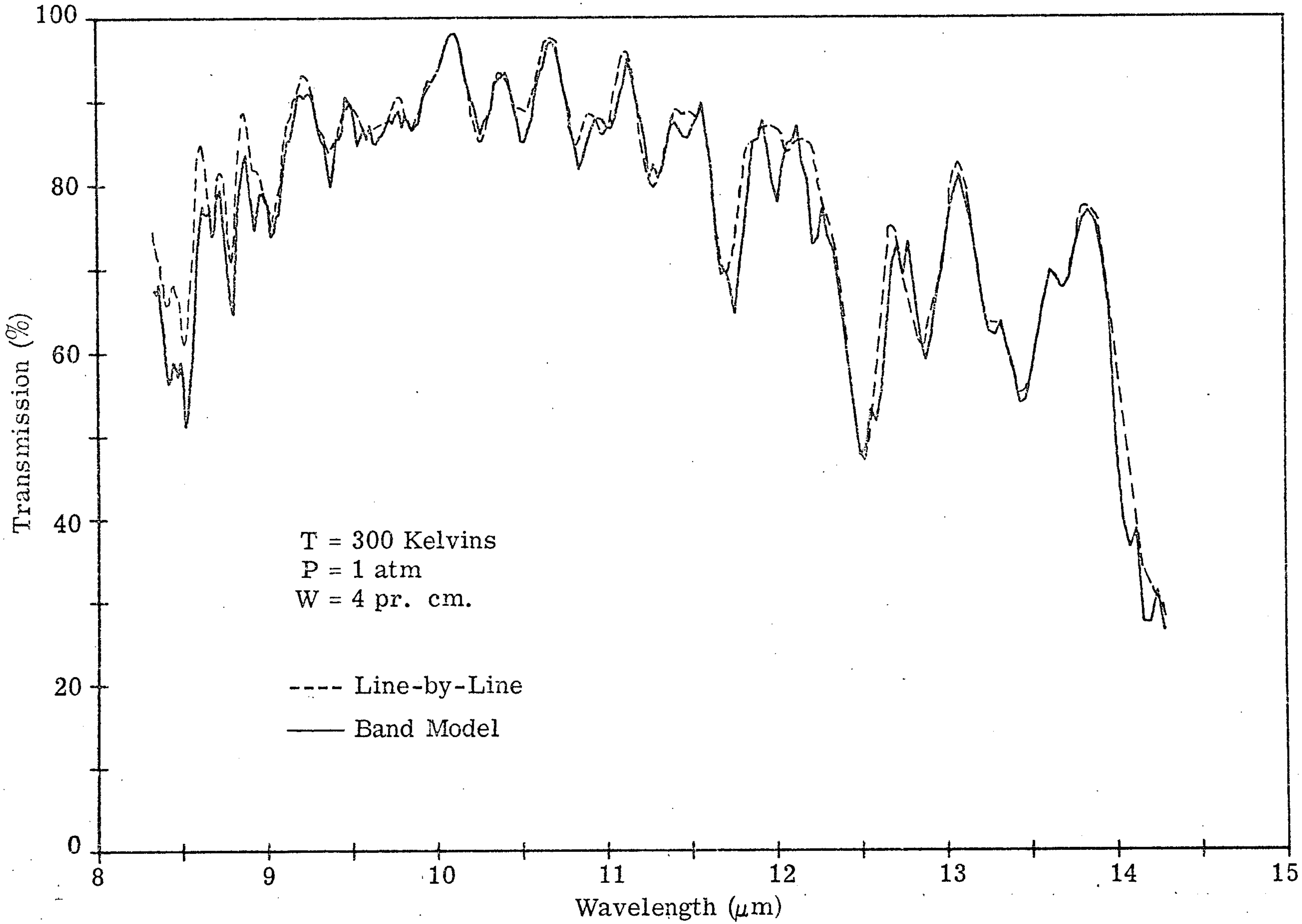

Figure 1. Comparison between Line-by-Line and Band Model Derived Spectra

2.1 Radiative Transfer Model Revision

There are two aspects of the model that required modification. These are the band model and associated coefficients which account for the effects of absorption and emission by local water vapor lines between 7 and 14 μm, and the coefficients which account for the effects of the H_2O continuum in the same spectral region.

The band model used to represent H_2O local line absorption was the Goody model which is given by [5]

$$\tau(\lambda) = \exp\left[\frac{-(S/d)\,W}{\sqrt{1 + \frac{2}{\overline{P}}\left(\frac{S}{2\pi\alpha}\right)W}}\right]$$

where

(S/d) = Intensity to line spacing parameter (cm^{-1})

W = Optical depth (pr. cm.)

$\overline{P}$ = Curtis Godson equivalent pressure (atm)

$\left(\frac{S}{2\pi\alpha}\right)$ = Intensity to halfwidth parameter ($atm\ cm^{-1}$)

The parameters S/d and $S/2\pi\alpha$ were evaluated from a tabulation of spectral parameters [6] using a procedure discussed by Goody [5], modified to account for a triangular instrument slit function. The parameters were evaluated at a spectral resolution of 10 cm^{-1} defined by the width of the slit function when the transmission is 50%. A comparison between band model and line-by-line derived spectra is shown in figure 1. In addition to a vast improvement in spectral resolution over the previous model, the model results are significantly improved quantitatively.

In the spectral region between 7 and 14 μm continuum absorption results from two mechanisms; that caused by the wings of water vapor lines within the 6.3 μm band and the rotational water band which are pressure broadened by foreign gases, and that caused by water vapor lines which are self-broadened. The continuum absorption coefficient at temperature T, total pressure P, and water vapor partial pressure p, is given by

$$k(T, P, p) = k_1 P + k_2 p$$

where

k_1 is the absorption coefficient for foreign broadening at unit total pressure;

k_2 is the coefficient for self-broadening at unit water vapor partial pressure.

The previous radiative transfer model did not consist of a two component coefficient and therefore, it could not properly represent the separate effects of foreign and self broadening.

The values of k_1 and k_2 adapted for the revised model are those of Kunde [7], based upon a subjective analysis of the data of Bignell [8, 9] and Burch [10], and investigations performed by Wark [11] and Houghton [12]. The adopted values are illustrated in figure 2.

The new band model for local line absorption and the revised model for the H_2O continuum were both incorporated into the previous radiative transfer model and calculations were compared with radiance measurements acquired by the Infrared Interferometer Spectrometer (IRIS) aboard Nimbus IV. The results are presented in figure 3. Within the spectral region of concern the differences are less than 5-10% in absolute value of spectral radiance.

2.2 Redefinition of Temperature Estimating Algorithms

As previously stated, estimating the temperature of the sea surface from radiometric data acquired in two spectral channels should provide

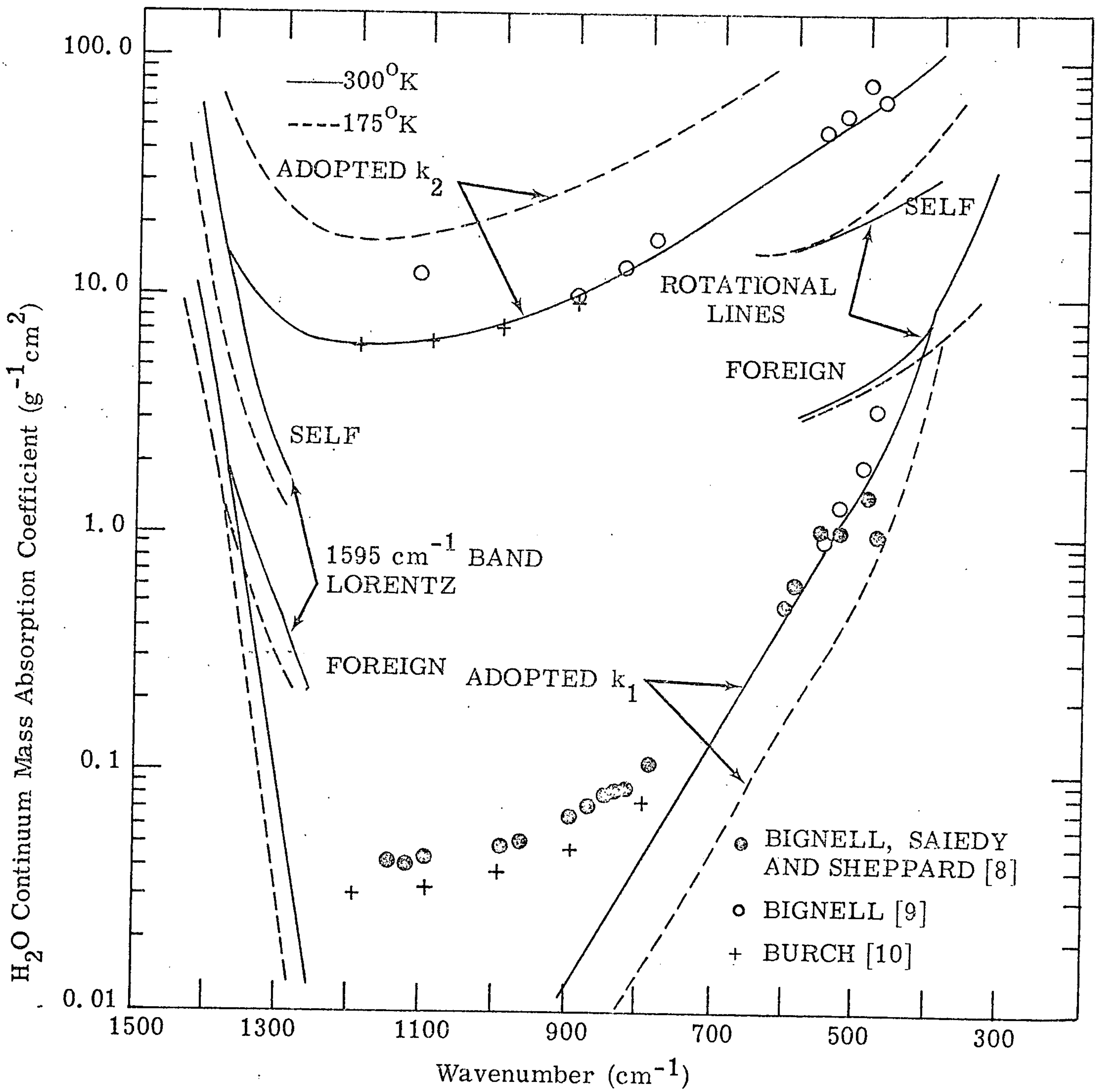

Figure 2. H_2O Continuum Coefficients [7]

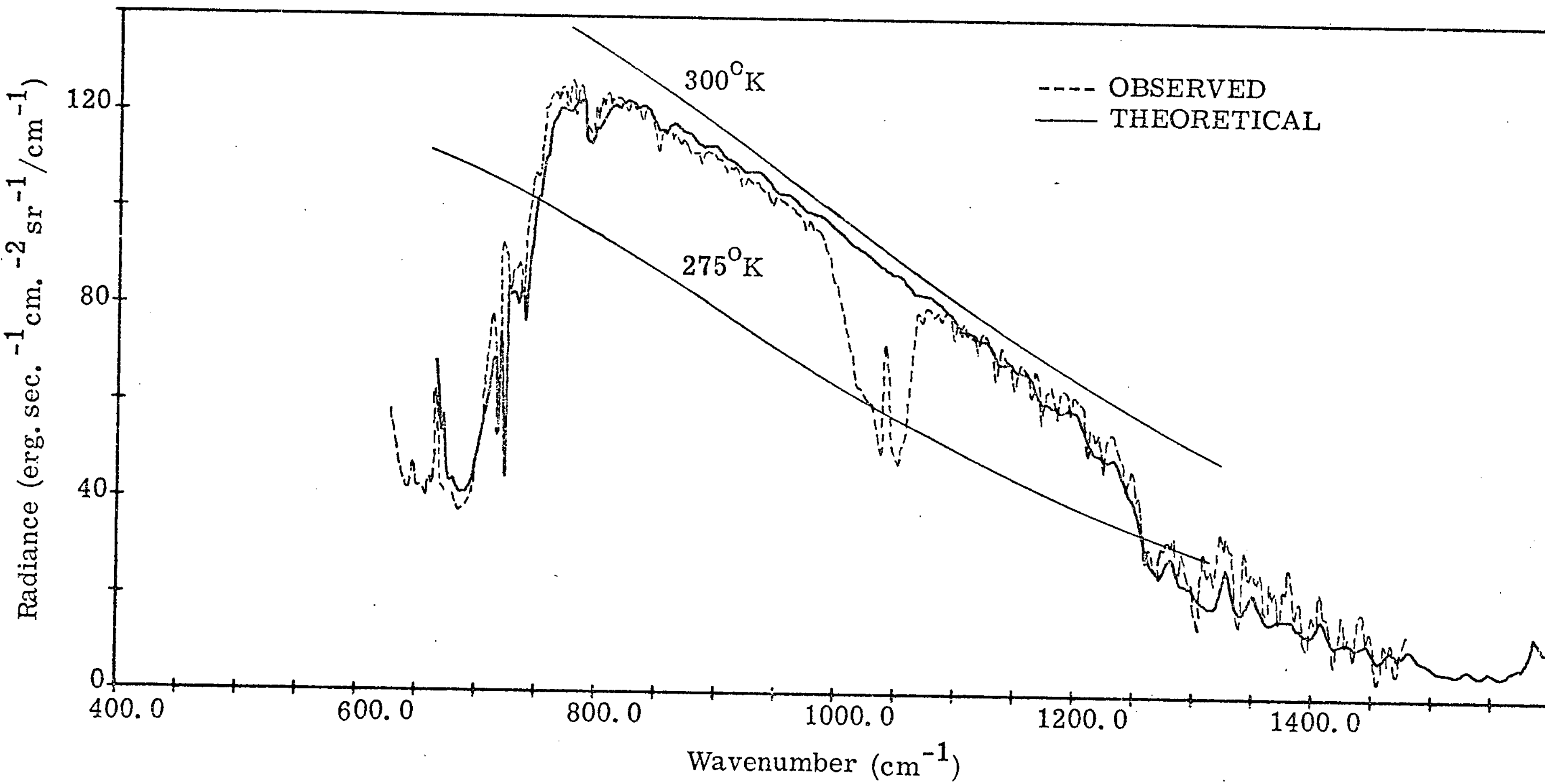

Figure 3. Upwelling Spectral Radiance at Space Altitudes as Measured by IRIS over Guam on 27 April 1970 Compared to Radiance Computed by Radiative Transfer Model. Ozone emission was neglected since ozone profile was unknown.

more accurate temperature estimates over those obtainable from a single channel measurement. The physical basis for this statement is demonstrated in figure 4, extracted from reference 2. The data presented were derived from the original radiative transfer model.

Presented is the relationship between radiance emanating at the top of the atmosphere, directed from a water surface, in two spectral bands centered at 9.1 μm and 11.0 μm, respectively. Each point on the curve represents radiance in these two bands for a given atmospheric state (i. e., air temperature and water vapor profile), for a given sea surface temperature and a given zenith viewing angle. Displayed are radiance pairs which are the result of many atmospheric states, zenith viewing angles and sea surface temperatures. For a given sea surface temperature, the data points are widely spread in either spectral band, demonstrating the errors inherent in a single band sea surface temperature estimate. However, it can be observed that a near linear relationship exists between the two band radiance values for a given sea temperature. Further, these lines are well separated for various sea surface temperatures. Therefore, a simultaneous measurement of the radiance in each of the two channels, together with the empirical linear relationships in figure 4, could be used to obtain improved estimates of sea temperatures over that obtainable from a single channel. The error in the estimate is determined by the scatter of data about the best fit lines shown in the figure, plus the addition of errors resulting from system calibration and system noise. It is precisely this postulate that is to be tested by the Skylab experiment. However, since the radiative transfer model used to calculate the data given in figure 4 has been significantly modified, it became necessary to redefine the two spectral channels, and the empirical relationship between these radiance values and sea surface temperature, prior to the analysis of S191 data in regard to algorithm verification. This was accomplished using the same model atmospheres, sea temperatures, and viewing geometries as used previously and the result is shown in figure 5.

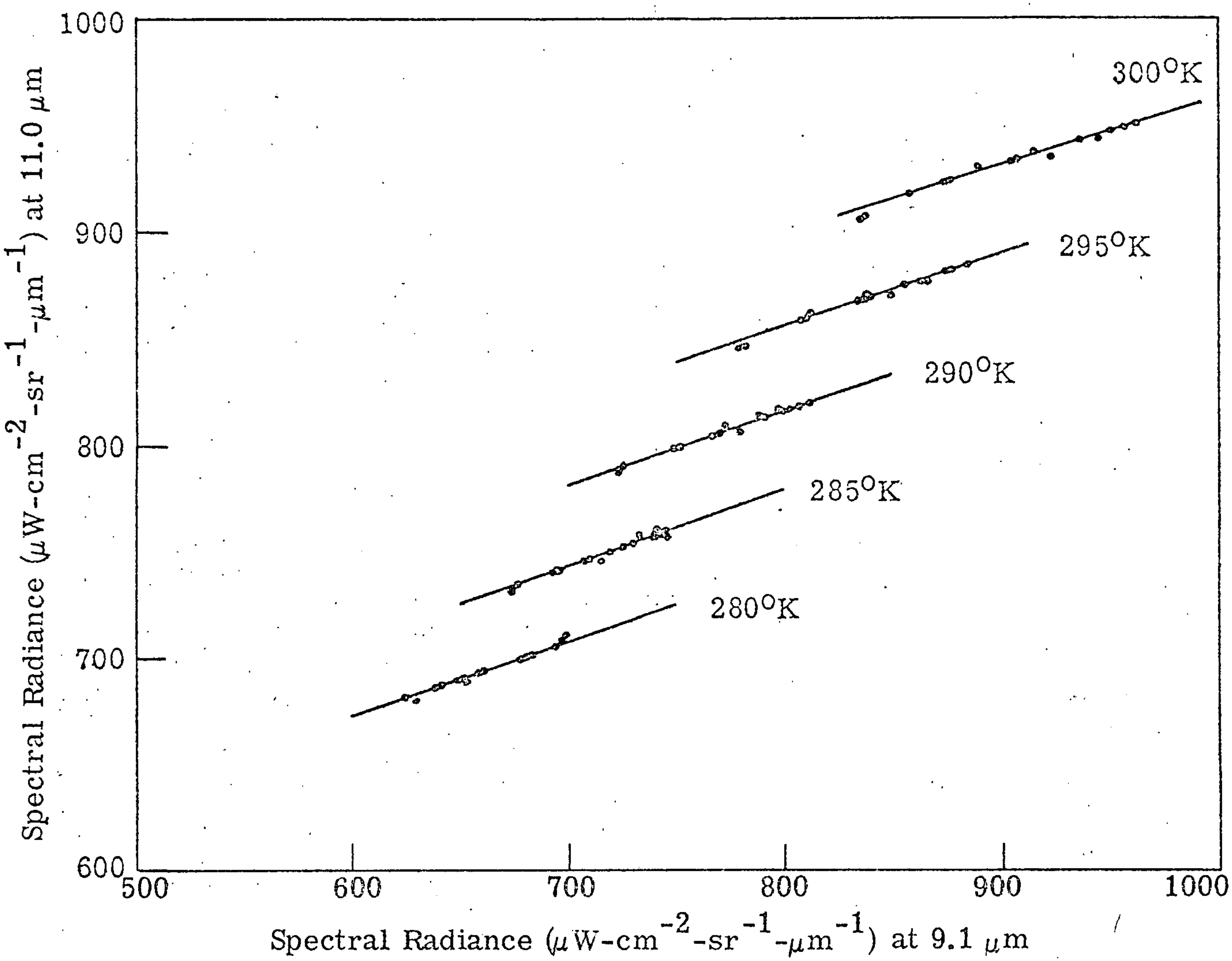

Figure 4. Spectral Radiance at 11.0 μm Versus that at 9.1 μm as a Function of Atmospheric State. Parameters = zenith angle at surface and sea-surface temperature.

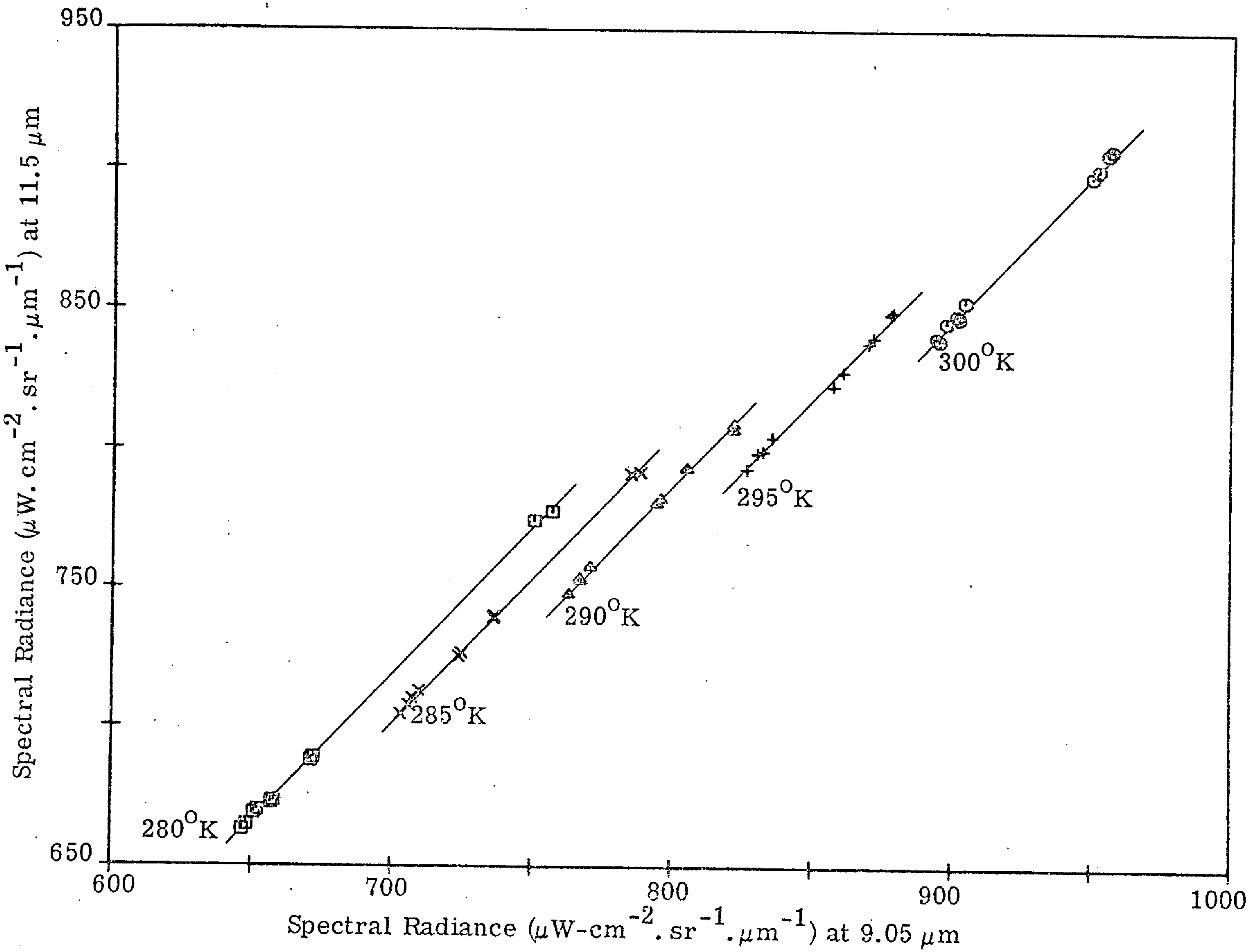

Figure 5. Spectral Radiance at 11.5 μm Versus that at 9.05 μm as a Function of Atmospheric State. Parameters = zenith angle at surface and sea-surface temperature.

Observe that the spectral channels which gave the best result in regard to minimum temperature error are different (centered at 9.05 and 11.5 μm respectively) than those derived previously. Also, the scatter in the data is somewhat increased, resulting in a slightly increased temperature error. The precise empirical relationship between these data was determined through the application of statistical linear regression.

The variables used in the regression were temperature, radiance* ($\mu W.cm^{-2}.sr^{-1}.\mu m^{-1}$) at 9.05 μm and 11.5 μm respectively, the square of each radiance value, and the product of the radiance values. When only a single spectral band is used to estimate temperature the standard error is approximately 2.25 K. The addition of the second spectral band reduced this error to approximately 0.54 K. The temperature algorithm for the two band case is

$$T = 276.6 + .252\, L_1 - .240\, L_2$$

where

T is temperature in Kelvins

L_1 is the 9.05 radiance value

and L_2 is the 11.5 radiance value.

The addition of the remaining three variables, L_1^2, L_2^2, and $L_1 * L_2$ reduces the standard error to approximately 0.31 K. The corresponding algorithm is

$$T = 429.82 + 1.194\, L_1 - 1.585\, L_2 + .00024\, L_1 L_2 + .0017\left(L_1^2 - L_2^2\right).$$

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*The actual value used was derived from; $L = \dfrac{\int L_\lambda \varphi(\lambda) d\lambda}{\int \varphi(\lambda) d\lambda}$

where $\varphi(\lambda)$ was a trapazoid filter function 1.2 μm wide.

It is the latter two algorithms which will be tested by the S191 experiment.

It is emphasized that these algorithms were derived from a restricted set of simulated data and are presented only for purposes of demonstrating the potential of the two band concept. The final selection of a two channel pair and the associated algorithm can only be made after completion of the Skylab experiment.

2.3 Software Development

In addition to the development of software required to modify the radiative transfer model and to redefine the sea temperature estimating algorithms, software necessary to process and analyze the data to be acquired during SL-2, SL-3, and SL-4 was developed.

The S191 data products to be received are: (a) S041-1, GMT correlated Radiance (tape), (b) S042-1, GMT correlated Boresight camera data (tabulation), and (c) GMT correlated radiosonde and surface truth data (tabulation). Basically two codes were developed, one for processing the received data products and one for analyzing the data. The processing code inputs all three data products, calculates the optical path between the spacecraft and ground target from ephemeris and ancillary data, processes radiosonde and surface truth data, categorizes radiance data according to optical path and stores with corresponding air, surface, and geometric data, and plots each radiance spectrum for visual inspection. The analysis code is composed of three separate codes; one for performing a statistical regression analysis on all spectral data to determine the two spectral bands which will yield the best estimates of sea surface temperatures; one for testing the two-band algorithms for clear atmospheres; and one for testing the radiative transfer model for clear and cloud-filled fields of view. Although all codes have been written and are operational, some further checking will be performed during the next quarter after a simulated S041-1 tape is received from the manned spacecraft center.

2.4 Travel Summary

During the first quarter one trip was taken to Goddard Spaceflight Center to visit Virgil Kunde for purposes of acquiring spectral line parameters and continuum coefficients for water vapor, and to discuss water vapor continuum absorption in general. It was these data that were used to redefine the band model parameters throughout the 7-15 μm region.

2.5 Future Plans

During each of the manned Skylab missions, SL-2, SL-3, and SL-4, S191 spectra will be acquired for cloud-free and cloud-filled fields of view for different viewing angles ranging from the nadir to 45 degrees forward of the spacecraft. Data will be acquired in the North Atlantic during SL-2 and SL-3 and in the Gulf of Mexico during SL-4. In all cases, supporting air and surface truth data will be acquired.

To demonstrate the nature of the data that will be obtained S191 data have been simulated, through the use of the revised radiative transfer model, for each of two viewing angles (0^{o} and 45^{o}) for cloud filled and cloud free fields of view. The results are given in figures 6 and 7. The sea surface and cloud temperatures were 300 and 273 Kelvins, respectively. Note that the atmosphere reduces the effective temperature of sea surface by approximately 3 kelvins at the nadir and approximately 4 Kelvins at a 45 degree nadir angle. For the cloud filled case, the atmospheric effect is negligible since little water vapor exists above the altitude of the cloud top. The model atmosphere used for these calculations was

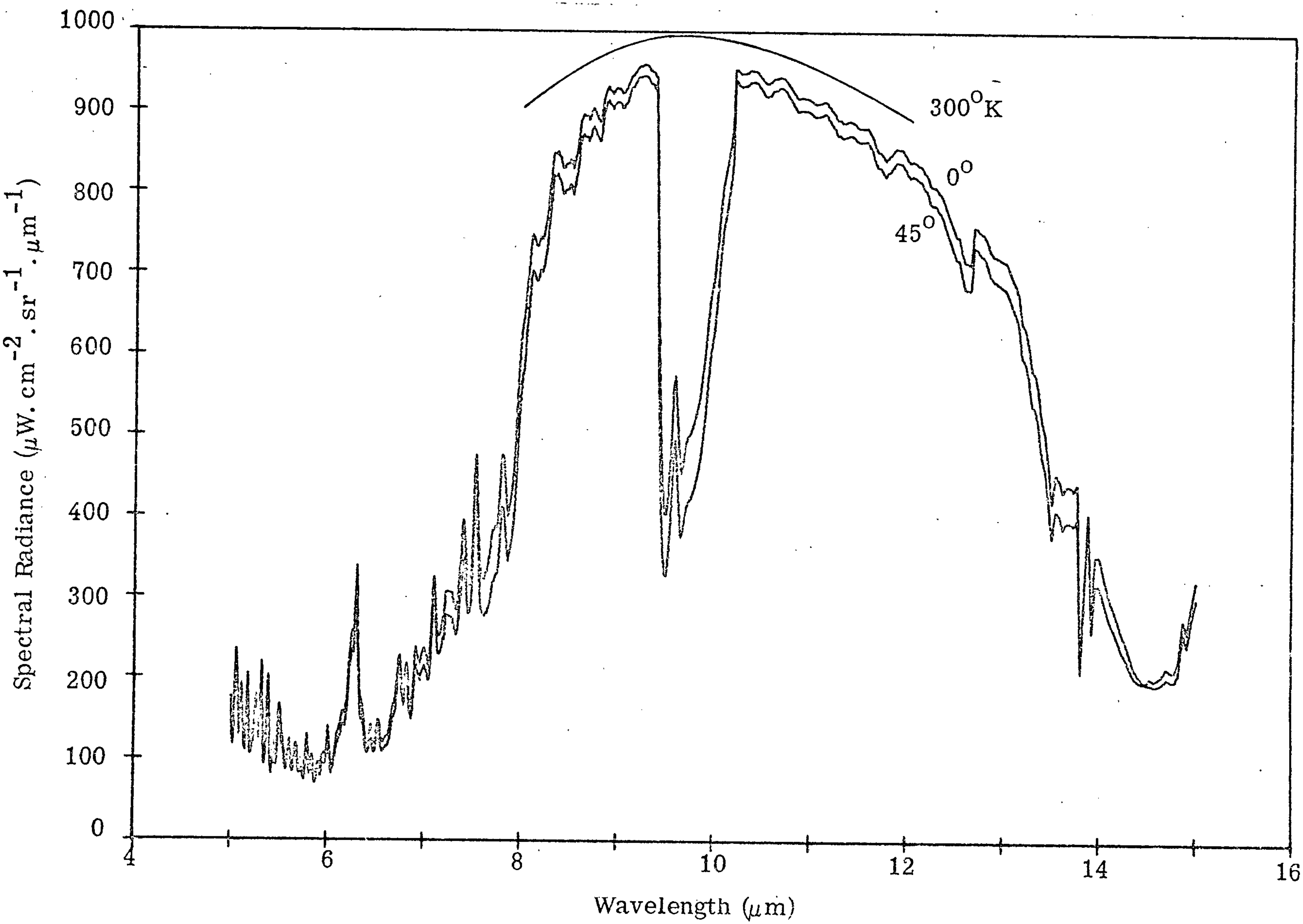

Figure 6. Upwelling Spectral Radiance at Skylab Altitude for Cloud Free F. O. V. Calculated by Radiative Transfer Model for Two Nadir Angles. Sea Surface Temperature = 300 Kelvins, Model Atmosphere = Summer Dry Conditions.

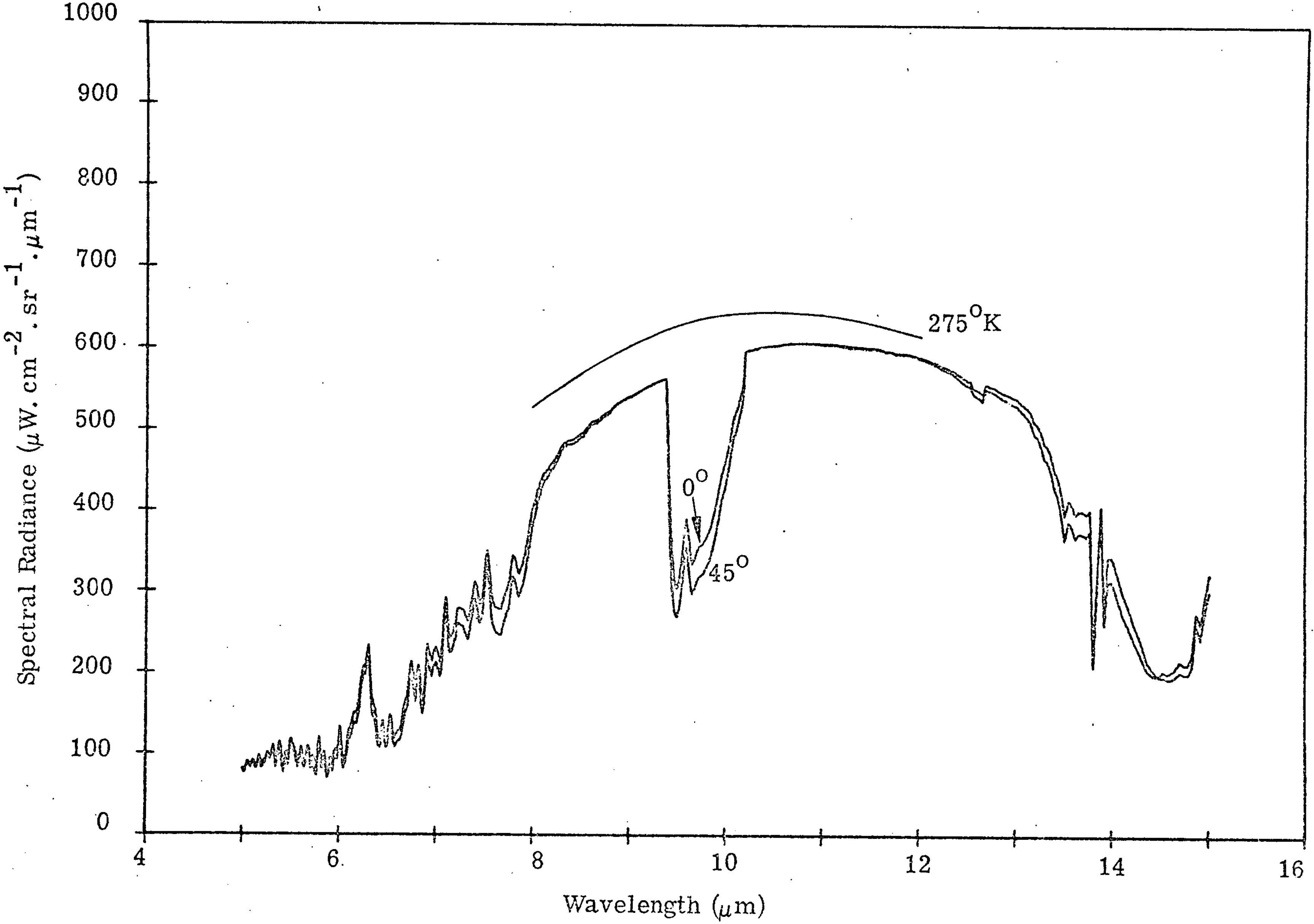

Figure 7. Upwelling Spectral Radiance at Skylab Altitude for Cloud Filled F. O. V. Calculated by Radiative Transfer Model for Two Nadir Angles. Cloud Altitude = 5 km, Cloud Temperature = 272.75 Kelvins, Model Atmosphere = Summer Dry Conditions.

moderately dry so the effect of the atmosphere on the brightness temperatures observed during the Skylab missions will, in general, be larger than that shown.

During the next quarter it is expected that data from SL-2 will have been received. These data will be processed, each of the three analysis functions stated in section 2. 3 will be performed, and the results presented in the second quarterly report.

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