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SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

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By

S.K. Gupta
and
S.N. Tiwari

NASA Contractor Report 158966

Final Report

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Under
Research Grant NSG 1282
Mr. John T. Suttles, Technical Monitor
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FOREWORD

This report constitutes the final part of the work completed on the research project "Determination of Atmospheric Pollutants from Infrared Radiation Measurements." The work was supported by the NASA/Langley Research Center through research grant NSG 1282. The grant was monitored by Mr. John T. Suttles of the Experiment Analysis Branch of the Atmospheric Environmental Sciences Division.

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GROUND TEMPERATURE MEASUREMENT BY

PRT-5 FOR MAPS EXPERIMENT

By

S.K. Gupta[1] and S.N. Tiwari[2]

SUMMARY

A simple algorithm and computer program have been developed for determining the actual surface temperature from the effective brightness temperature as measured remotely by a radiation thermometer called PRT-5. This procedure allows the computation of atmospheric correction to the effective brightness temperature without performing detailed radiative transfer calculations. Model radiative transfer calculations are performed to compute atmospheric corrections for several values of the surface and atmospheric parameters individually and in combination. Polynomial regressions were performed between the magnitudes or deviations of these parameters and the corresponding computed corrections to establish simple analytical relations between them. Analytical relations have also been developed to represent combined correction for simultaneous variation of parameters in terms of their individual corrections. These analytical relations can be used in all future work to determine the actual surface temperature without having to perform expensive radiative transfer calculations. Model calculations have also been made to examine the sensitivity of the retrieved surface temperatures to uncertainties in the various surface and atmospheric parameters.

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1. INTRODUCTION

Measurement of concentrations of gaseous atmospheric pollutants like CO, CH_4, NH_3 and SO_2 is of great importance because of their considerable effect on various natural processes affecting human health, environment and meteorology [1]*. Successful attempts have been made recently, to measure several of these pollutants by passive remote-sensing instruments mounted on aircraft [2,3] with the intention of eventually adapting them to satellite use. These instruments measure the upwelling infrared radiation in an appropriate spectral region, which in turn carries the signature of the particular pollutant molecules [4].

Extraction of the pollutant concentrations from these measured signals requires, in addition to sophisticated data reduction algorithms [5], prior knowledge of several parameters of the atmosphere as well as the underlying surface. The atmospheric parameters, e.g., pressure, temperature and humidity profiles can be obtained either from additional instruments mounted aboard the aircraft itself or from other independent sources (e.g., radiosondes). The surface parameters, namely, the emittance and temperature are not available from any such sources. Any meaningful physical contact measurement of these parameters is not feasible because of the vast areas covered in remote sensing experiments and large spatial variations of the quantities involved. Reliable estimates of surface emittance, however, can be obtained from an approximate knowledge of the color, texture and composition of the surface. This is possible because extensive tabulation relating basic characteristics of the surfaces to their emittance values are available in the literature [6]. This leaves the surface temperature as the important unknown quantity to be determined.

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*Numbers in brackets indicate references.

The work presented in this report was performed in support of the project MAPS (Measurement of Air Pollution from Satellites) at the Langley Research Center. Current work under this project involves frequent flights of a gas-filter correlation radiometer (GFCR) on an aircraft. This instrument is designed to measure carbon monoxide concentration in the troposphere. A radiation thermometer called PRT-5 (Precision Radiation Thermometer-5, Barnes Engineering Company, Stamford, Connecticut) is flown alongside the GFCR for measuring the temperature of the underlying surface. This latter instrument is essentially a broad-band radiometer which operates in the 11 micron atmospheric window. Under certain ideal conditions, namely (i) when the emittance of the target surface is unity, and (ii) when the attenuation by the atmosphere between the target surface and the sensor is negligible, this instrument can directly read the surface temperature.

These ideal conditions, however, are always far from being met in the real world situations. In addition to the deviation of surface emittance from unity, line and continuum absorption by water vapor in this region [7,8] introduce error in the temperature measurement by PRT-5, which needs to be determined and corrected for. A strong temperature dependence of the continuum absorption coefficient [8,9] introduces additional uncertainty in this measurement. Anding and Kauth [10] and Prabhakara et al. [11] have discussed the use of differential absorption by water vapor in adjacent spectral regions to correct for the attenuation due to water vapor. Since PRT-5 is a single-channel, non-dispersive instrument, the above technique is not applicable in the present case.

The purpose of the present study is to develop algorithms and software for computing correction to the measured surface temperature arising from the above-mentioned causes. The attenuation due to water vapor absorption may be evaluated accurately using a line-by-line radiative transfer model.

Routine data reduction using line-by-line model tends to be extremely expensive [12] and, therefore, inexpensive algorithms have to be developed to determine the magnitude of the correction. This can be done by performing some model calculations and using those results to establish simple analytical relations between the magnitudes and deviations of the parameters from their standard values and the corresponding corrections required to compensate for them. These relations can then be used in the future to compute the corrections for any set of parameters without performing detailed radiative transfer calculations.

Relevant theory and the development of algorithm is presented in Section 2. Data sources and computation procedure are referred to in Section 3. Results of the model calculations are discussed in Sections 4 and 5. Application of the algorithm is presented in Section 6. Section 7 contains results of some sensitivity calculations. Important conclusions of this work are discussed in Section 8.

2. THEORY AND ALGORITHM

The quantity measured by any broad-band radiometer is the integrated, upwelling radiance which for a homogeneous nonscattering atmosphere can be expressed as [4,13]

$$E = \int_{\omega_1}^{\omega_2} E_G(\omega)\ f(\omega)\ d\omega \tag{2.1}$$

where ω_1 and ω_2 represent the frequency limits of the observed spectral region and $f(\omega)$ is the instrument filter function. $E_G(\omega)$ represents the monochromatic thermal radiance emitted by the underlying surface and the atmosphere and is given by

$$E_G(\omega) = \varepsilon(\omega)\ B(\omega, T_s)\ \tau(\omega, 0) + \int_0^h B[\omega, T(z))\ [d\tau(\omega, z)/dz]\ dz \tag{2.2}$$

where $\varepsilon(\omega)$ is the surface emittance, $B(\omega, T)$ is the Planck's blackbody radiance for temperature T, T_s is the surface temperature, $T(z)$ is the temperature at altitude z, and $\tau(\omega, z)$ is the monochromatic transmittance of the atmosphere. The first term on the right-hand side of equation (2.2) represents the radiation from the surface while the second term represents the radiation originating in the atmosphere. Solar radiation reflected from the surface and the scattered radiation make negligible contribution to the upwelling radiance in the 11 micron region.

The quantity measured by a direct-reading instrument like the PRT-5 is the effective brightness temperature (EBT) of the surface, denoted by T_e and is defined as

$$\int_{\omega_1}^{\omega_2} B(\omega, T_e)\ f(\omega)\ d\omega = E \tag{2.3}$$

where the black-body radiance corresponding to T_e equals the total upwelling radiance. Simple inversion of equation (2.3) for radiometrically measured values of E would yield T_e for any given altitude and set of surface and atmospheric conditions. Inversion of equation (2.1) to extract the actual surface temperature T_s, on the other hand, would involve detailed radiative transfer calculations. Furthermore, the accuracy requirements of the atmospheric problems necessitate the use of line-by-line model for transmittance computation [14].

2.1 Analytical Formulation

The need to perform line-by-line radiative transfer calculations for every set of surface and atmospheric conditions may be eliminated by performing some model calculations and establishing relations between T_s, T_e and the magnitudes or deviations of the input (surface as well as atmospheric) parameters. Since T_e is equal to T_s for surface emittance equal to unity and no water vapor in the atmosphere, these are adopted as the initial conditions. The quantities which give rise to the difference between T_e and T_s (i.e., the correction denoted by ΔT) are the magnitude of water vapor burden and the deviation of surface emittance (ε) from unity. Analytical relations will be established, therefore, between the above quantities and the resulting corrections ΔT. The correction may be expressed as

$$\Delta T = T_e - T_s \tag{2.4}$$

where T_e is obtained by inverting equation (2.3). Since radiometrically measured values of E cannot be obtained for all the desired conditions for establishing the necessary relations, they are computed from equation (2.1) for a series of values of the surface temperature, T_s and several values of each of the input parameters.

Gupta and Tiwari [15] analyzed the magnitudes of corrections to EBT caused by deviations of various input parameters for radiometric measurements made in the 4.66 micron region and found that the correction ΔT can usually be expressed in terms of the deviation Δx (of the parameter x) by simple analytical functions. For most cases, these relationships may be represented by a polynomial as

$$\Delta T = \sum_{n=o}^{N} a_n (\Delta x)^n \tag{2.5}$$

where N is a positive integer. The first few terms of this polynomial should adequately represent the correction ΔT for the expected range of the deviations Δx. The coefficients a_n can be obtained by polynomial regression in the results obtained from model calculations. Future computations of ΔT can then be made from a_n and Δx without having to perform the lengthy radiative transfer calculations. Results of the model calculations for the deviation of a single parameter and their analysis is presented in Sec. 4.

A more complicated situation arises when more than one input parameters undergo simultaneous deviations. The combined correction, to be denoted by ΔT_c may be represented as a function of the individual corrections. For example, if Δx and Δy represent deviations of two input parameters x and y from their initial values, the combined correction may be expressed as

$$\Delta T_c = f(\Delta T_x, \Delta T_y) \tag{2.6}$$

where ΔT_x and ΔT_y represent the individual corrections caused by the deviations Δx and Δy separately. Additional model calculations have been performed to examine the nature of the above function for different sets of parameters. Results of these calculations and their analysis are presented in Sec. 5.

2.2 Water Vapor Absorption

The total absorption coefficient $k_t(\omega)$ for water vapor in the 11 micron window may be expressed as [9,11]

$$k_t(\omega) = k_\ell(\omega) + k_p(\omega)\ (p-p_{H_2O}) + k_e(\omega\ \ p_{H_2O} \tag{2.7}$$

where

$k_\ell(\omega)$ - absorption coefficient due to water vapor lines,

$k_p(\omega)$ - continuum absorption coefficient due to pressure broadening by other gases,

$k_e(\omega)$ - continuum absorption coefficient due to self-broadening, and

p, p_{H_2O} - the total pressure and partial pressure of water vapor respectively.

Absorptions represented by k_p and k_e are also called the p-type and e-type absorptions respectively. Measurements of k_p and k_e are reported by several workers [7,8]. Roberts et al. [9] reviewed these and other recent laboratory measurements by Burch and reanalyzed a bulk of field measurements [16] to conclude that in the vicinity of 300°K, k_p is very small compared to k_e . The total absorption may, therefore, be expressed as

$$k_t(\omega) = k_\ell(\omega) + k_e(\omega)\ p_{H_2O} \tag{2.8}$$

A strong negative temperature dependence of k_e was observed by Bignell [8] and Burch [7]. Roberts et al. [9] have analyzed the above temperature dependence data and that from several other workers and have shown that

$$k_e(\omega) = k_e^o(\omega)\ \exp[T_o(\frac{1}{T} - \frac{1}{296})] \tag{2.9}$$

gives the value of $k_e(\omega)$ at the temperature T , where $k_e^o(\omega)$ refers to a temperature of 296°K and the best estimate of T_o is found to be 1800°K.

The frequency variation of $k_e^o(\omega)$ in the 8-12 micron region was also studied by Roberts et al. from an analysis of the experimental data from the various available sources, Roberts et al. [9] have developed an empirical representation which can be expressed as

$$k_e^o(\omega) = a + b \exp(-\beta\omega) \tag{2.10}$$

where the constants a, b and β are

$$a = 1.25 \times 10^{-22} \text{ mol}^{-1} \text{ cm}^2 \text{ atm}^{-1},$$

$$b = 2.34 \times 10^{-19} \text{ mol}^{-1} \text{ cm}^2 \text{ atm}^{-1},$$

and

$$= 8.30 \times 10^{-3} \text{ cm}.$$

It has been pointed out by the authors that while equation (2.10) can be used for the entire region up to 30 microns, the temperature dependence expressed by equation (2.9) may not be valid far beyond the 8-12 micron region.

3. DATA SOURCES AND COMPUTATION PROCEDURE

The model atmosphere adopted for the present work is essentially the U.S. Standard Atmosphere, 1962 and the water vapor profile is approximately an average of winter and summer mid-latitude distributions [17]. Since other minor atmospheric constituents (e.g., CO_2, N_2O) are inactive in this spectral region, they were excluded from consideration in the model atmosphere as well as the radiative transfer.

For the present work performed to support aircraft observations, troposphere up to an altitude of 17,500 ft. was considered and was divided into ten layers of unequal thicknesses. Pressure, temperature and water vapor concentration for these layers are given in Table 3.1. The altitudes at the layer boundaries are listed in the first column of the table. Data in the next three columns represent the averages for layers between the altitudes just below and above these values.

Table 3.1

Model Atmosphere used for the Study.

Altitude (ft)	Pressure (mm Hg)	Temperature (°K)	Water Vapor Conc. (10^3 ppmV)
0			
	763.16	287.66	7.626
500			
	742.65	286.17	7.240
1,500			
	716.03	284.19	6.726
2,500			
	677.55	281.22	5.972
4,500			
	628.87	277.26	5.100
6,500			
	583.07	273.30	4.222
8,500			
	540.03	269.34	3.338
10,500			
	499.59	265.38	2.669
12,500			
	461.66	261.42	2.074
14,500			
	417.57	256.48	1.493
17,500			

Spectral parameters of individual lines of water vapor in the 9.8-13.2 micron (1020-760 cm^{-1}) region were obtained from the AFCRL line parameter compilation [18], and were used in evaluating the line component of the absorption coefficient using line-by-line model. The information presented in Sec. 2 was utilized to evaluate the continuum component (self-broadened) of the absorption coefficient.

Integrated upwelling radiance was computed using equation (2.1). Radiative transfer calculations were performed using total absorption coefficient obtained by combining the line and continuum components. Effective brightness temperature is obtained by inversion of equation (2.3) using quadratic interpolation. The instrument filter function as supplied by the manufacturer is shown in Fig. 3.1 and was used in radiance calculation after digitization. A computer program named PRTFIVE has been developed to accomplish the above objectives and is listed in Appendix B. It evaluates in a single run, the integrated upwelling radiance and therefrom the EBT for eight values of actual surface temperature from 290 to 325°K and for ten different altitudes at the top of each of the ten layers. Program runs were made for several values of each of the parameters covering realistic ranges for their variations. Analytical relations were developed by carrying out regression in the tables of Δx and corresponding tables of ΔT for the various parameters. Starting from a linear fit, higher degree fits were attempted if the magnitudes of the residuals between the computed values and those obtained from the fit exceeded 0.1°K.

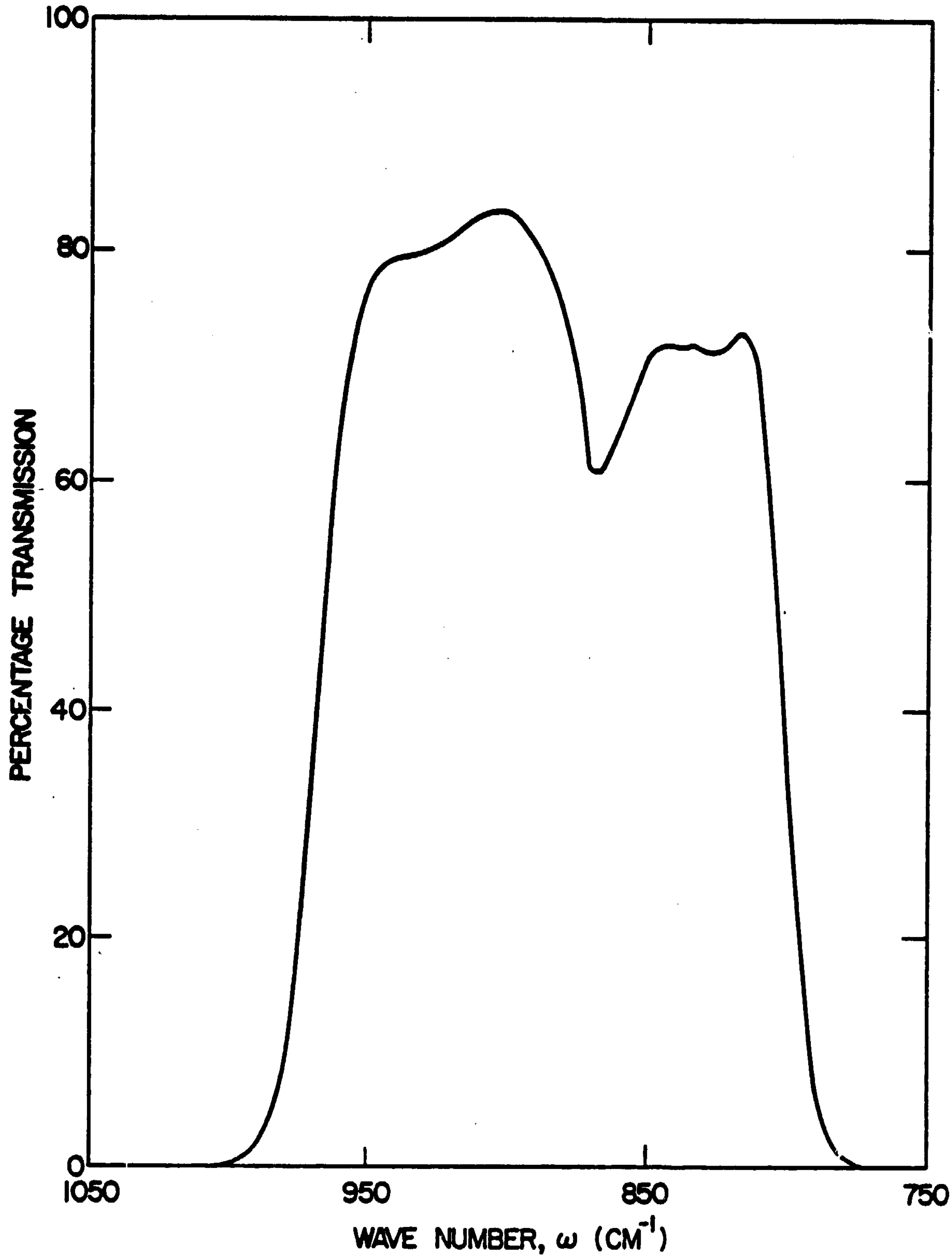

Fig. 3.1 The PRT-5 filter function.

4. MODEL CALCULATIONS FOR ONE PARAMETER

The input parameters considered important for this study are (i) surface emittance, (ii) water vapor distribution, and (iii) atmospheric temperature profile. Model calculations have been performed and analyzed for deviation of a single parameter at a time and also for simultaneous deviations of more than one parameter. Results obtained for deviations of a single parameter are discussed in this section. Discussion of the results obtained for simultaneous variation of two parameters is covered in the next section. The corrections for each value of the parameters are obtained for eight values of the actual surface temperature, T_s and for all ten altitudes.

4.1 Surface Emittance

Integrated upwelling radiance and EBT were evaluated for five values of surface emittance between 1.00 and 0.80. Computations have been made in absence of any water vapor in the atmosphere as well as in presence of a standard water vapor burden. The dry atmosphere results are presented first and Table 4.1 lists the values of EBT and corrections for all eight values of T_s for this case. Since there is no attenuation of radiation in the atmosphere in this case, these values of EBT and correction are independent of the altitude. Figure 4.1 shows the magnitudes of the correction as a function of the deviation of emittance for T_s = 300, 310, and 320°K. Polynomial regression in these data and those for other values of T_s shows that these results can be adequately represented by quadratic expressions. The coefficients of quadratic regression, a_0, a_1 and a_2 were determined for all values of T_s. It can be seen from figure 4.1 that all these curves pass through the origin and hence, the coefficient a_0 is insignificantly small in all cases. The significant coefficients a_1 and a_2 for all values

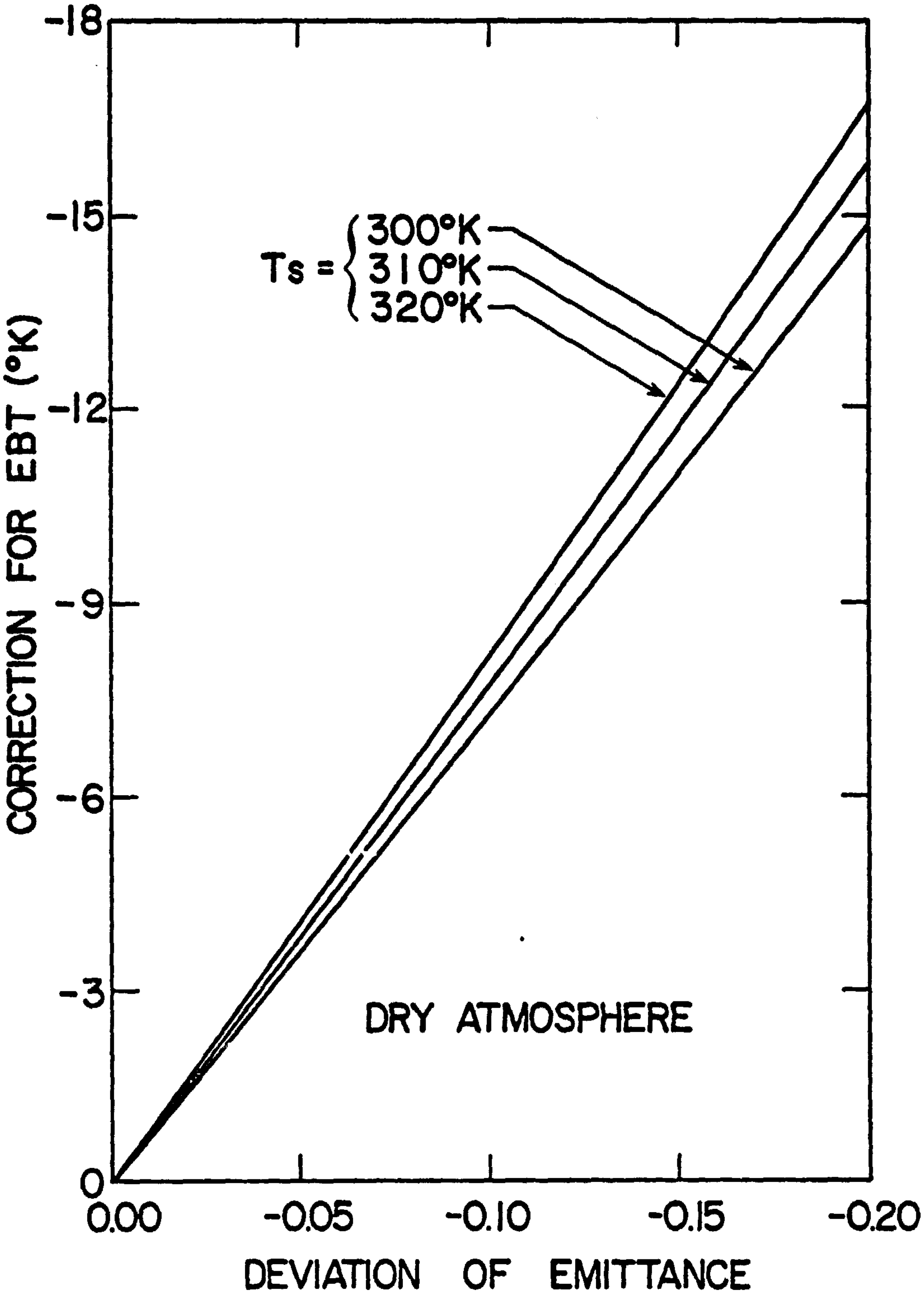

Fig. 4.1 Variation of correction with the deviation of emittance for the dry atmosphere.

Table 4.1

Effective brightness temperature and correction as a function of surface emittance for a dry atmosphere.

Actual Surface Temp. (°K)	Effective Brightness Temp. and Correction (°K)				
	ε = 1.00	ε = 0.95	ε = 0.90	ε = 0.85	ε = 0.80
290	290.000	286.688	283.271	279.748*	276.120*
	0.000	-3.312	-6.729	-10.252	-13.880
295	295.000	291.577	288.047	284.408	280.643
	0.000	-3.423	-6.953	-10.592	-14.357
300	300.000	296.465	292.821	289.065	285.181
	0.000	-3.535	-7.179	-10.935	-14.819
305	305.000	301.351	297.594	293.717	289.712
	0.000	-3.649	-7.406	-11.283	-15.288
310	310.000	306.236	302.362	298.364	294.237
	0.000	-3.764	-7.638	-11.636	-15.763
315	315.000	311.119	307.126	303.007	298.756
	0.000	-3.881	-7.874	-11.993	-16.244
320	320.000	316.001	311.887	307.649	303.270
	0.000	-3.999	-8.113	-12.351	-16.730
325	325.000	320.881	316.646	312.283	307.777
	0.000	-4.119	-8.354	-12.717	-17.223

*Values obtained by extrapolation.

of T_s are presented in Table 4.2 and it shows that both coefficients are dependent on the actual surface temperature, T_s . Figure 4.2 depicts the variation of a_1 and a_2 with actual surface temperature.

<u>Table 4.2</u>

Regression coefficients a_1 and a_2 as functions of the actual surface temperature for the emittance variation study in a dry atmosphere.

Actual Surface Temp. (°K)	a_1	a_2
290	65.183	-21.086
295	67.235	-22.657
300	69.447	-23.143
305	71.666	-23.771
310	73.939	-24.286
315	76.251	-24.743
320	78.573	-25.257
325	80.934	-25.771

Computations in the presence of a standard water vapor burden (or wet atmosphere) were also made for all eight values of T_s and all ten altitudes. Because of attenuation due to atmospheric water vapor, the EBT changes with the altitude in this case. Values of EBT and the correction for all values of T_s and the altitude of 17,500 ft. are listed in Table 4.3. Differences between T_s and the values of T_e which correspond to $\varepsilon = 1.00$ are due to the attenuation of the surface radiation by the atmospheric water vapor. Corrections due to deviation of emittance are, therefore, obtained by subtracting the values in the second column from those in columns 3-6 of this table and are listed right under the T_e values.

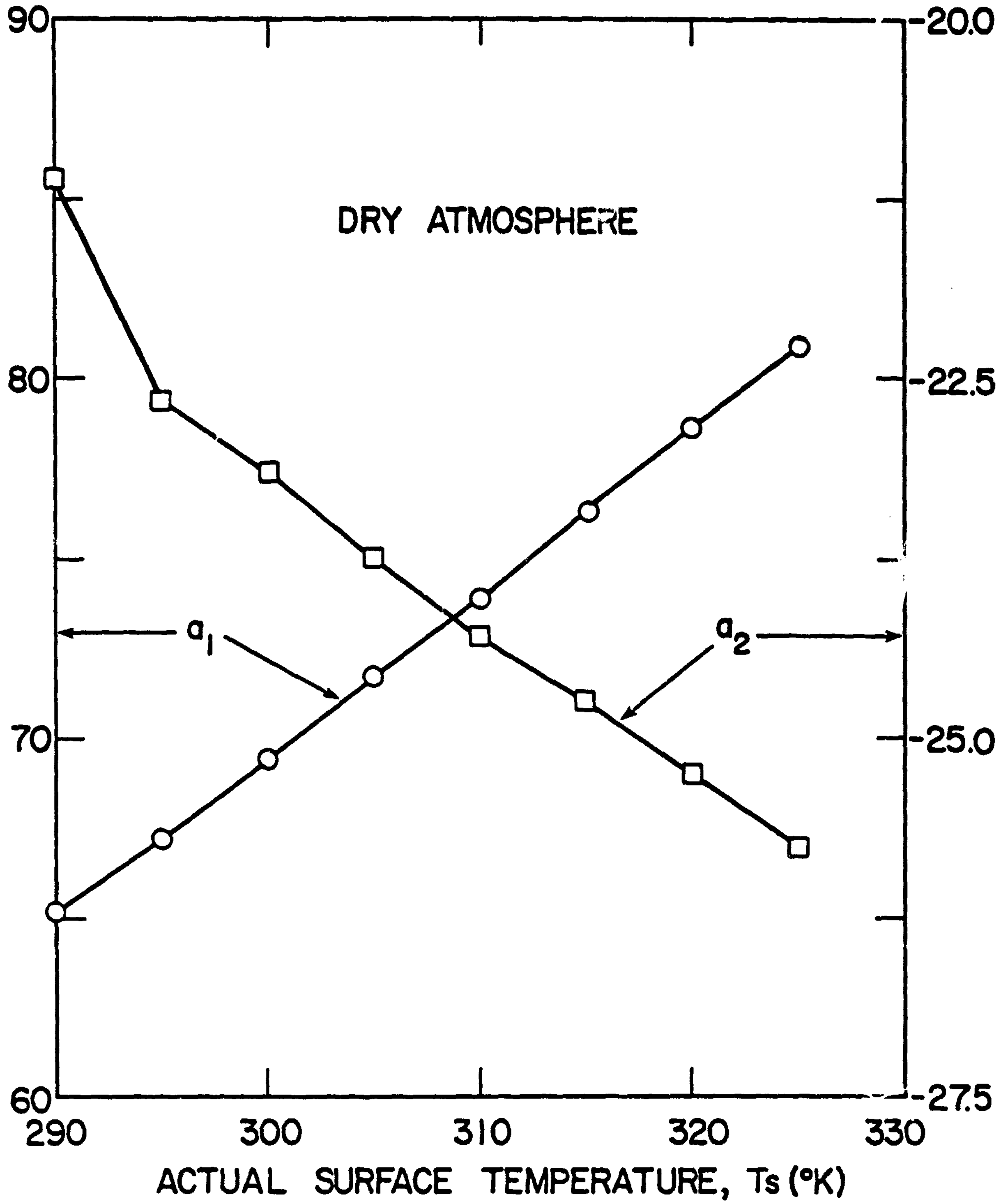

Fig. 4.2 Variation of regression coefficients a_1 and a_2 with actual surface temperature for the dry atmosphere.

Table 4.3

Effective brightness temperature and correction as a function of surface emittance for an altitude of 17,500 ft.

Actual Surface Temp. (°K)	Effective Brightness Temperature (°K)				
	ε = 1.00	ε = 0.95	ε = 0.90	ε = 0.85	ε = 0.80
290	288.501	285.600	282.617	279.556*	276.415*
	0.000	-2.901	-5.884	-8.945	-12.086
295	292.910	289.898	286.805	283.620	280.343
	0.000	-3.012	-6.105	-9.290	-12.567
300	297.341	294.214	291.006	287.707	284.306
	0.000	-3.127	-6.335	-9.634	-13.035
305	301.786	298.546	295.223	291.806	288.282
	0.000	-3.240	-6.563	-9.980	-13.504
310	306.246	302.893	299.453	295.917	292.275
	0.000	-3.353	-6.793	-10.329	-13.971
315	310.719	307.255	303.696	300.040	296.275
	0.000	-3.464	-7.023	-10.679	-14.444
320	315.205	311.625	307.949	304.172	300.283
	0.000	-3.580	-7.256	-11.033	-14.922
325	319.700	316.006	312.214	308.313	304.300
	0.000	-3.694	-7.486	-11.387	-15.400

*Values obtained by extrapolation.

Figure 4.3 shows the values of the temperature correction as a function of the deviation of surface emittance for the altitude of 17,500 ft. and three values of T_s, 300, 310 and 320°K. Polynomial regression in these data shows again the curves can be represented by quadratic expressions with residues much smaller than the acceptable 0.1°K. The regression coefficients a_o, a_1 and a_2 were determined for all values of T_s and the altitude and all a_o are insignificant for the reason mentioned earlier. The coefficients a_1 and a_2 are presented in Table 4.4. This table shows again that both coefficients a_1 and a_2 are dependent on the surface temperature, T_s as well as the altitude. As illustrations, the variation of these coefficients with T_s for the altitude of 17,500 ft. is shown in Figure 4.4. Figure 4.5 shows the variation of these coefficients with altitude for T_s = 300°K.

It is important to note that the emittance correction determined here for the wet atmosphere case has to be combined with the correction due to the presence of water vapor. As a result, the total correction is this case is given by

$$\Delta T = \Delta T_\varepsilon + \Delta T_w \tag{4.1}$$

where ΔT_ε is the correction determined from the coefficients given in Table 4.4 and ΔT_w corresponds to the presence of standard water vapor burden.

4.2 Water Vapor Distribution

The water vapor is an important absorbing constituent for infrared radiation in the troposphere and is the only absorber in the spectral region of this instrument. Its variation, therefore, has significant effect on the correction to EBT and is considered in two ways. These are (i) increasing or decreasing water vapor concentration as multiples of the standard water vapor profile in all layers, and (ii) increasing concentration in some layers

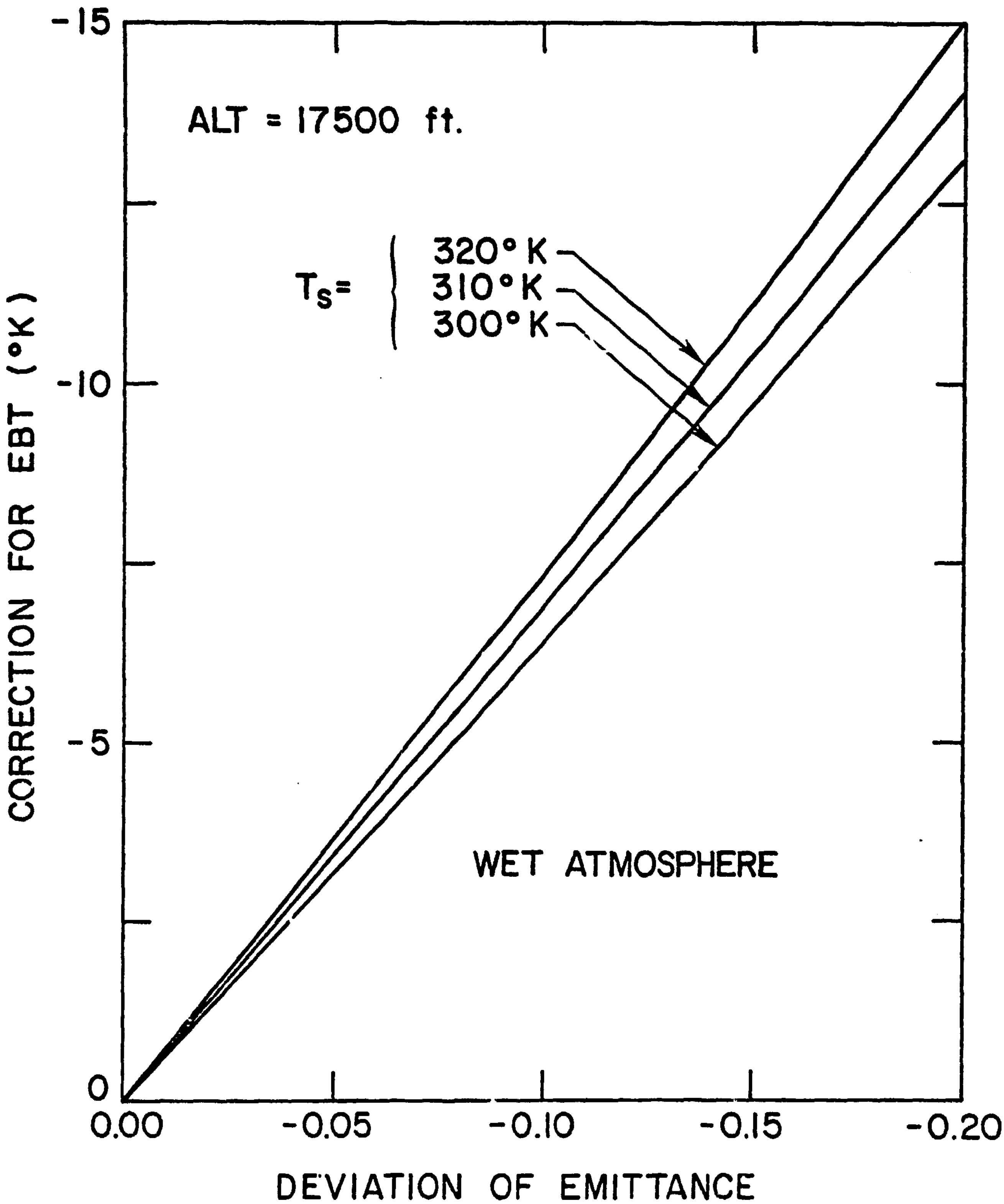

Fig. 4.3 Variation of correction with the deviation of emittance for the wet atmosphere from 17,500 ft.

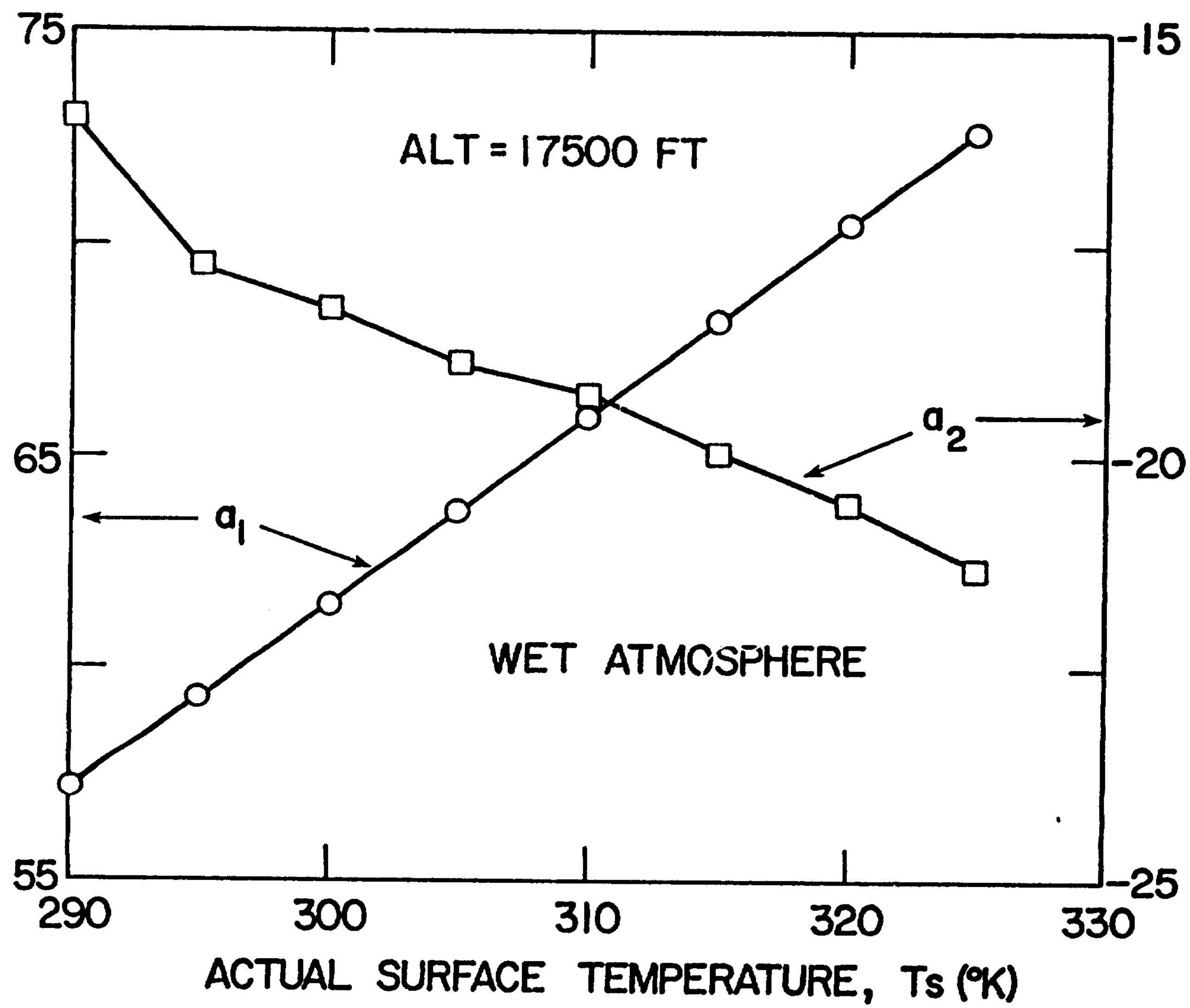

Fig. 4.4 Variation of regression coefficients a_1 and a_2 with actual surface temperature for the wet atmosphere and 17,500 ft.

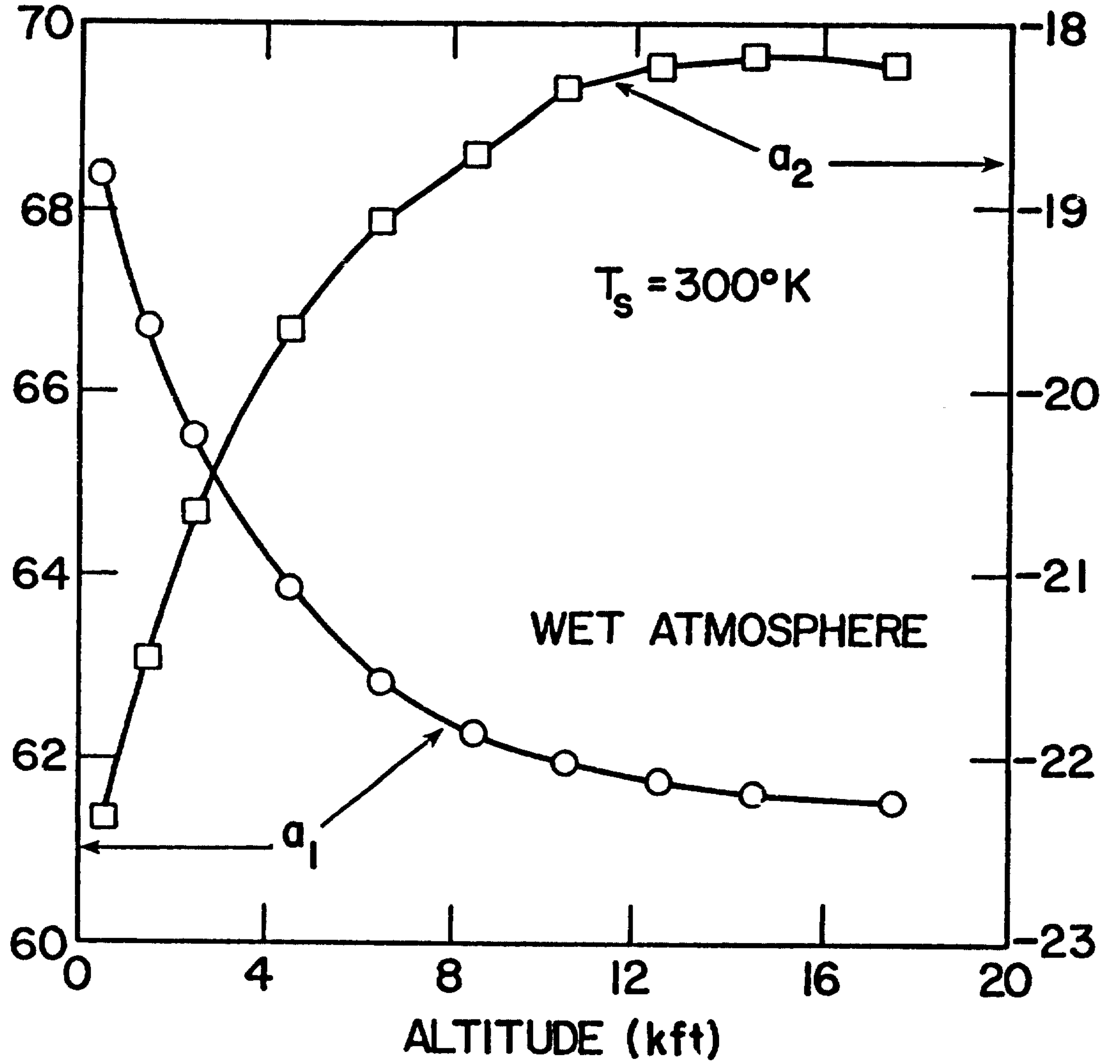

Fig. 4.5 Variation of regression coefficients a_1 and a_2 with altitude for the wet atmosphere and T_s = 300°K.

Table 4.4

Regression coefficients a_1 and a_2 are functions of actual surface temperature and altitude for surface emittance study.

Altitude (ft.)	Regression Coefficients							
	290°K	295°K	300°K	305°K	310°K	315°K	320°K	325°K
500	64.056	66.117	68.352	70.563	72.841	75.147	77.461	79.859
	-20.357	-21.916	-22.333	-23.044	-23.551	-24.047	-24.610	-24.871
1500	62.404	64.484	66.685	68.935	71.209	73.487	75.836	78.216
	-19.302	-20.802	-21.441	-21.996	-22.536	-23.144	-23.476	-23.872
2500	61.196	63.286	65.488	67.735	69.981	72.277	74.620	76.994
	-18.541	-20.011	-20.671	-21.248	-21.897	-22.429	-22.769	-23.164
4500	59.572	61.625	63.865	66.107	68.345	70.694	72.997	75.316
	-17.525	-19.189	-19.670	-20.269	-20.934	-21.146	-21.695	-22.252
6500	58.568	60.619	62.853	65.062	67.362	69.660	71.949	74.244
	-16.894	-18.571	-19.074	-19.778	-20.191	-20.564	-21.139	-21.787
8500	57.961	60.007	62.235	64.485	66.734	69.024	71.292	73.586
	-16.505	-18.203	-18.725	-19.262	-19.843	-20.227	-20.891	-21.480
10500	57.617	59.660	61.931	64.129	66.399	68.647	70.918	73.176
	-16.276	-17.995	-18.353	-19.070	-19.457	-20.122	-20.718	-21.458
12500	57.418	59.458	61.725	63.920	66.186	68.430	70.697	72.949
	-16.137	-17.874	-18.244	-18.963	-19.349	-20.022	-20.623	-21.367
14500	57.309	59.346	61.611	63.803	66.067	68.308	70.572	72.821
	-16.056	-17.808	-18.187	-18.906	-19.292	-19.970	-20.574	-21.320
17500	57.234	59.269	61.502	63.721	65.983	68.221	70.482	72.730
	-15.995	-17.761	-18.257	-18.870	-19.257	-19.938	-20.544	-21.291

while decreasing in others such that the total water vapor burden in the atmosphere under consideration remains unaltered.

Computations of correction to the EBT were made for six multiples of the water vapor profile, namely, 0.0, 0.25, 0.5, 1.5, 2.0 and 3.0 in addition to the standard profile itself, for all values of T_s and the altitude. Table 4.5 lists the values of EBT and corresponding corrections for all values of T_s and the altitude of 17,500 ft. Results for this altitude and $T_s = 300$, 310 and 320°K were chosen for graphical illustration and are shown in Figure 4.6. Polynomial regression in these results between Δx (water vapor burden) and ΔT(correction) reveals that cubic expressions are required to adequately represent these relationships. Regression coefficients a_o, a_1, a_2 and a_3 were determined for all cases and a_o are found to be insignificant again. Coefficients a_1, a_2 and a_3 are presented in Table 4.6 and are entered together for each value of T_s and the altitude. It can be seen from this table that all these coefficients are functions of T_s as well as the altitude. Figure 4.7 shows the variation of a_1, a_2 and a_3 with T for the altitude of 17,500 ft. Variation of these coefficients wi h altitude for $T_s = 300$°K is shown in Figure 4.8.

The effect of redistribution of water vapor in the atmosphere (without changing the total water vapor burden) has been studied by generating two modifications of the standard water vapor profile. Modification A is generated by arbitrarily decreasing the water vapor burden in the lower five layers and increasing the burden by the same amount in the upper five layers. Modification B is generated by an exactly opposite operation. Table 4.7 shows a layer-by-layer distribution of water vapor burden for the standard and modified profiles.

Table 4.5

Effective brightness temperature as a function of water vapor burden for an altitude of 17,500 ft.

Actual Surface Temp.(°K)	Effective Brightness Temperature (°K)						
	0.00	0.25	0.50	1.00	1.50	2.00	3.00
290	290.000	289.682	289.348	288.501	287.404	286.088	283.060
	0.000	-0.318	-0.652	-1.499	-2.596	-3.912	-6.940
295	295.000	294.561	294.097	292.910	291.363	289.523	285.387
	0.000	-0.439	-0.903	-2.090	-3.637	-5.477	-9.613
300	300.000	299.443	298.856	297.341	295.354	292.998	287.759
	0.000	-0.557	-1.144	-2.659	-4.646	-7.002	-12.241
305	305.000	304.330	303.622	301.786	299.371	296.515	290.181
	0.000	-0.670	-1.378	-3.214	-5.629	-8.485	-14.819
310	310.000	309.220	308.394	306.246	303.414	300.061	292.645
	0.000	-0.780	-1.606	-3.754	-6.586	-9.939	-17.355
315	315.000	314.113	313.173	310.719	307.482	303.638	295.146
	0.000	-0.887	-1.827	-4.281	-7.518	-11.362	-19.856
320	320.000	319.008	317.957	315.205	311.566	307.245	297.688
	0.000	-0.992	-2.043	-4.795	-8.434	-12.755	-22.312
325	325.000	323.908	322.748	319.700	315.669	310.875	300.261
	0.000	-1.092	-2.252	-5.300	-9.331	-14.125	-24.739

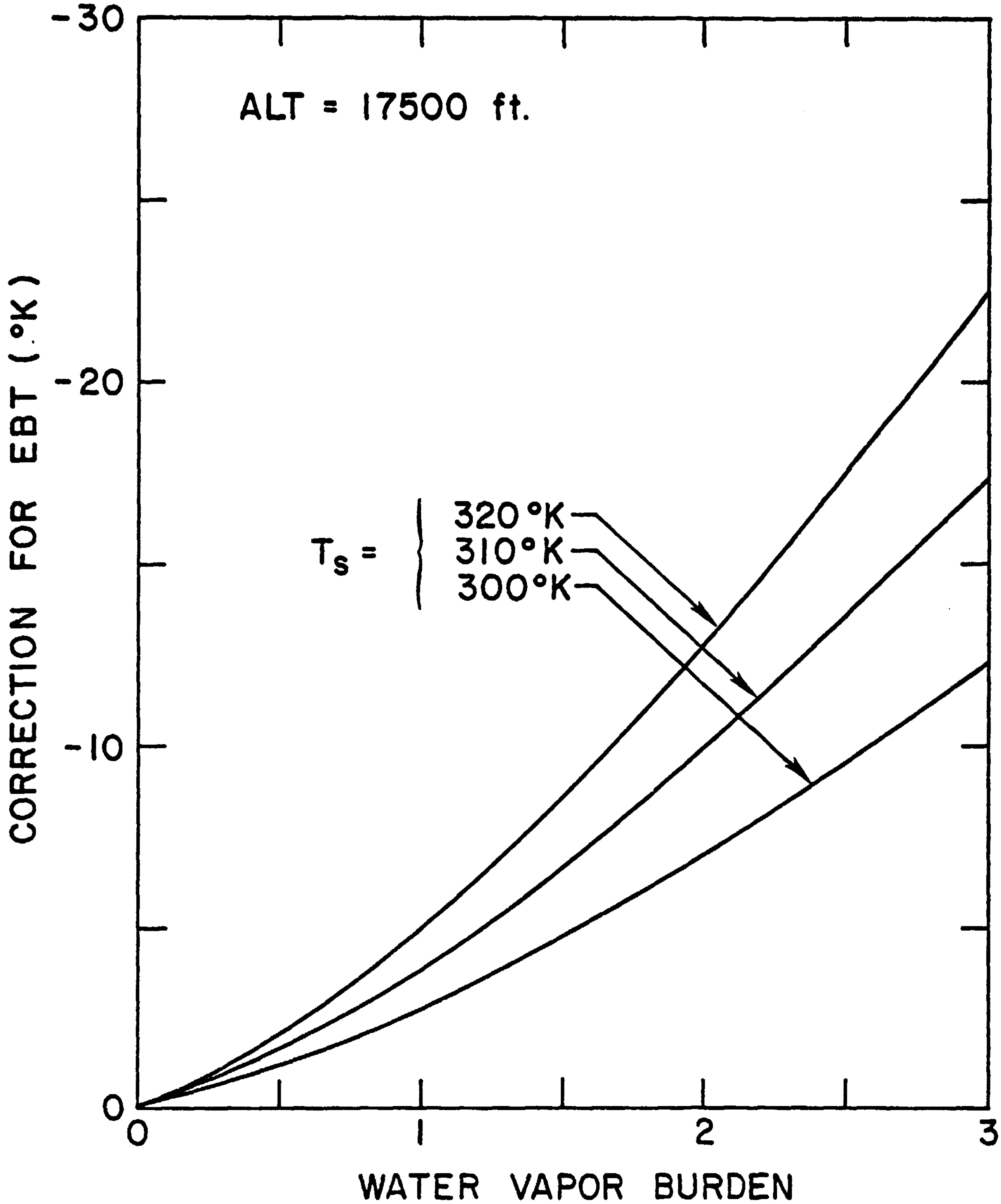

Fig. 4.6 Variation of correction with water vapor burden from 17,500 ft.

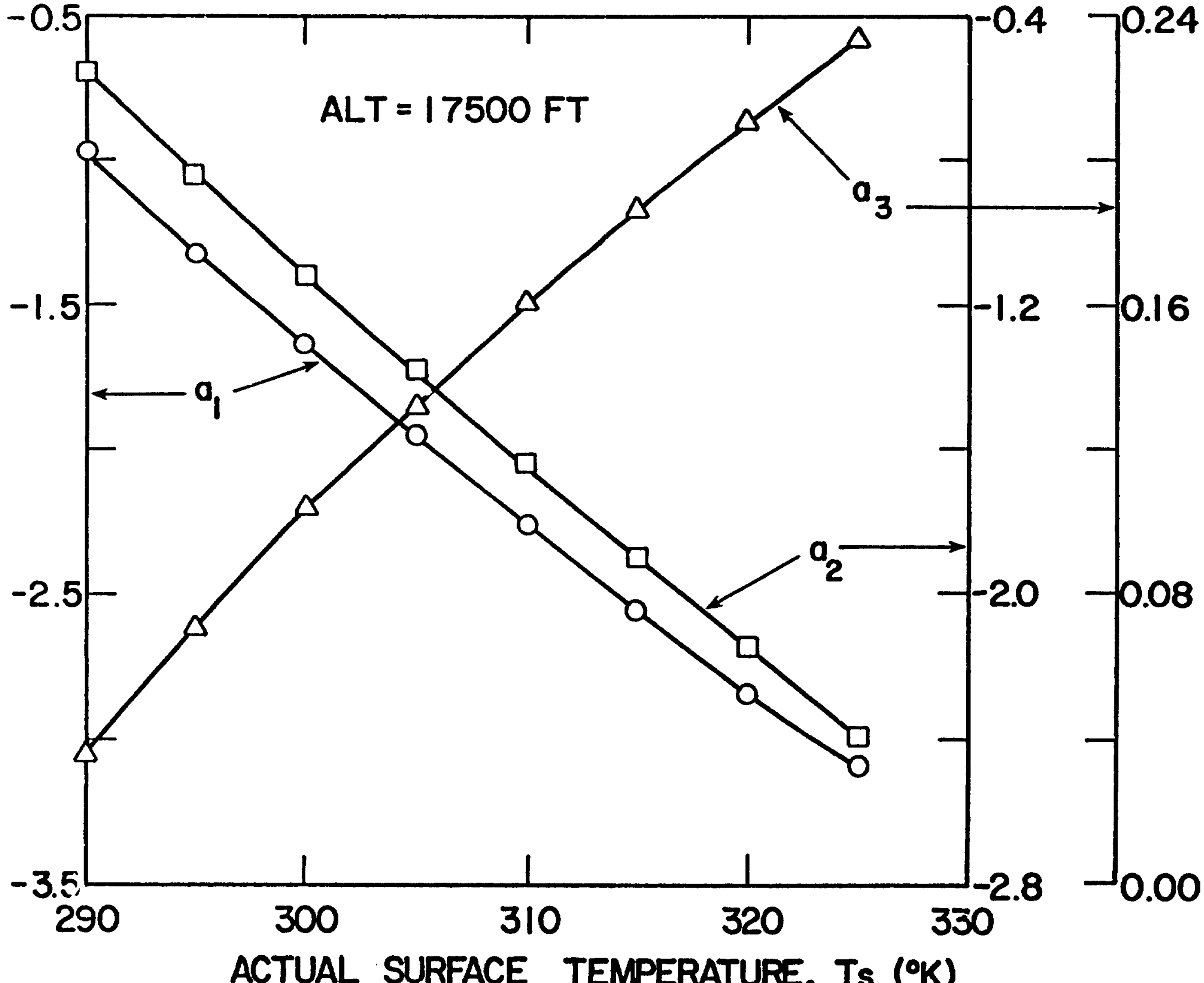

Fig. 4.7 Variation of regression coefficients a_1, a_2 and a_3 with actual surface temperature for 17,500 ft.

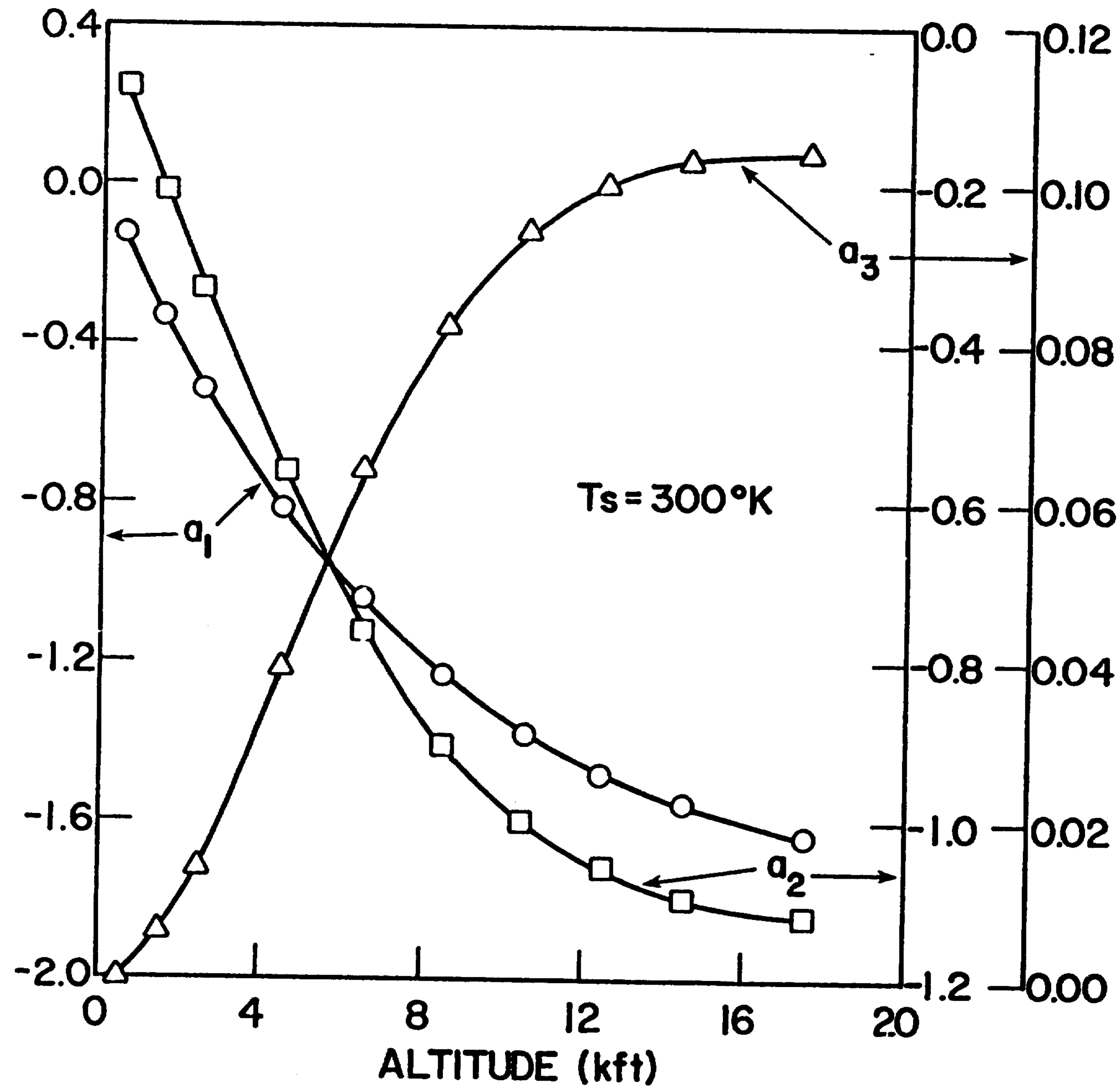

Fig. 4.8 Variation of regression coefficients a_1, a_2 and a_3 with altitude for T_s = 300°K.

Table 4.6

Regression coefficients a_1, a_2 and a_3 as functions of actual surface temperature and altitude for water vapor burden study.

Altitude (ft)	Regression Coefficients							
	290°K	295°K	300°K	305°K	310°K	315°K	320°K	325°K
500	-0.025	-0.076	-0.127	-0.173	-0.219	-0.264	-0.307	-0.349
	-0.015	-0.047	-0.075	-0.105	-0.133	-0.160	-0.187	-0.211
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1500	-0.088	-0.216	-0.338	-0.457	-0.574	-0.686	-0.792	-0.892
	-0.054	-0.133	-0.211	-0.283	-0.350	-0.418	-0.486	-0.554
	0.001	0.004	0.006	0.007	0.007	0.008	0.009	0.011
2500	-0.165	-0.345	-0.523	-0.692	-0.853	-1.008	-1.162	-1.306
	-0.103	-0.223	-0.332	-0.441	-0.548	-0.654	-0.754	-0.857
	0.004	0.010	0.014	0.018	0.022	0.026	0.029	0.033
4500	-0.327	-0.579	-0.820	-1.047	-1.270	-1.482	-1.697	-1.900
	-0.215	-0.392	-0.563	-0.735	-0.898	-1.060	-1.210	-1.363
	0.013	0.027	0.039	0.051	0.062	0.072	0.080	0.089
6500	-0.488	-0.780	-1.054	-1.321	-1.573	-1.827	-2.071	-2.307
	-0.326	-0.545	-0.763	-0.972	-1.182	-1.376	-1.569	-1.761
	0.023	0.044	0.064	0.082	0.100	0.115	0.129	0.144
8500	-0.635	-0.943	-1.241	-1.524	-1.807	-2.077	-2.341	-2.594
	-0.410	-0.664	-0.908	-1.149	-1.375	-1.600	-1.819	-2.036
	0.029	0.057	0.082	0.106	0.127	0.147	0.166	0.184
10500	-0.751	-1.072	-1.378	-1.682	-1.973	-2.254	-2.528	-2.799
	-0.470	-0.741	-1.005	-1.253	-1.499	-1.739	-1.972	-2.199
	0.034	0.065	0.094	0.119	0.143	0.166	0.188	0.208
12500	-0.841	-1.173	-1.486	-1.797	-2.094	-2.381	-2.665	-2.942
	-0.511	-0.790	-1.063	-1.321	-1.576	-1.826	-2.066	-2.301
	0.036	0.069	0.100	0.127	0.153	0.178	0.200	0.222
14500	-0.912	-1.245	-1.563	-1.878	-2.181	-2.473	-2.763	-3.040
	-0.534	-0.820	-1.099	-1.361	-1.619	-1.872	-2.114	-2.359
	0.037	0.071	0.103	0.131	0.158	0.183	0.206	0.229
17500	-0.983	-1.322	-1.641	-1.960	-2.265	-2.561	-2.852	-3.134
	-0.551	-0.839	-1.121	-1.386	-1.649	-1.904	-2.152	-2.397
	0.036	0.071	0.104	0.132	0.160	0.186	0.210	0.233

Table 4.7

Water Vapor distribution for standard and modified profiles.

Layer No.	Water Vapor Burden (cm-atm)		
	Standard	Mod. A	Mod. B
1	110.75	100.75	120.75
2	205.72	190.72	220.72
3	185.53	174.53	196.53
4	315.07	303.08	327.08
5	253.31	249.32	257.32
6	197.24	201.24	193.24
7	146.56	156.56	136.56
8	110.03	120.04	100.04
9	80.20	90.20	70.20
10	79.84	97.83	61.83

Effective brightness temperatures have been obtained for all values of T_s and the altitude of 17,500 ft. corresponding to the modified water vapor profiles and are presented along with the standard profile results in Table 4.8 The altitude of 17,500 ft. has been selected here so that the observed effect is as large as possible. Comparison of the EBT values presented in Table 4.8 shows that except for the highest value of T_s, the differences between the EBT values corresponding to the standard and modified profiles are always smaller than 0.1°K.

Table 4.8

Effective brightness temperature for standard and modified water vapor profiles at 17,500 ft.

Actual Surface Temp. (°K)	Eff. Brightness Temp. (°K)		
	Standard	Mod. A	Mod. B
290	288.501	288.453	288.541
295	292.910	292.883	292.926
300	297.341	297.334	297.335
305	301.786	301.798	301.759
310	306.246	306.277	306.197
315	310.719	310.768	310.650
320	315.205	315.271	315.115
325	319.700	319.784	319.592

4.3 Atmospheric Temperature Profile

Variations of atmospheric temperature distribution are expected to have significant effect on the upwelling radiance and the EBT in this spectral region, particularly because of the strong temperature dependence of the continuum absorption coefficient [8,9]. This effect was examined quantitatively by adopting four additional temperature profiles for the atmosphere. Since the temperature gradient in the troposphere is relatively constant, profiles with fixed biases of +2, +1, -1, and -2°K relative to the standard were considered as realistic variations.

Effective brightness temperature for all values of T_s and altitudes were obtained corresponding to the above temperature profiles. Since variations of temperature profile become meaningless in absence of any water vapor, these computations have been carried out in the presence of a standard water vapor burden. EBT values for an altitude of 17,500 ft. are presented in Table 4.9. Corrections in this case are obtained relative to the EBT values which correspond to the standard temperature profile and are listed just below the EBT values in the same table. The differences between T_s and T_e values which correspond to the standard temperature profile are again due to the presence of water vapor.

Figure 4.9 shows the correction as a function of the temperature bias for two altitudes (4,500 and 17,500 ft.) and $T_s = 300$°K. Regression in these data shows that these results can be adequately represented by linear expressions. Coefficients of regression a_o and a_1 were determined for all cases. It is again clear from Fig. 4.9 that all these lines pass through the (o,o) point and, therefore, the coefficients a_o are insignificant. The coefficient a_1 for all values of T_s and altitude are presented in Table 4.10. Figure 4.10 shows the coefficient a_1 as a function of T_s for the altitudes of 4,500 and 17,500 ft. It can be seen from this figure as well as from

Table 4.9

Effective brightness temperature for different atmospheric temperature profile for the altitude 17,500 ft.

Actual Surface Temp(°K)	Effective Brightness Temperature (°K)				
	Atmospheric Temperature Profiles				
	T' = T-2	T' = T-1	T' = T	T' = T+1	T' = T+2
290	288.235	288.369	288.501	288.630	288.758
	-0.266	-0.132	0.000	0.129	0.257
295	292.644	292.777	292.910	293.041	293.169
	-0.266	-0.133	0.000	0.131	0.259
300	297.068	297.206	297.341	297.474	297.603
	-0.273	-0.135	0.000	0.133	0.262
305	301.509	301.649	301.786	301.920	302.051
	-0.277	-0.137	0.000	0.134	0.265
310	305.965	306.107	306.246	306.382	306.515
	-0.281	-0.139	0.000	0.136	0.269
315	310.433	310.578	310.719	310.857	310.992
	-0.286	-0.141	0.000	0.138	0.273
320	314.914	315.061	315.205	315.344	315.481
	-0.291	-0.144	0.000	0.139	0.276
325	319.405	319.555	319.700	319.842	319.981
	-0.295	-0.145	0.000	0.142	0.281

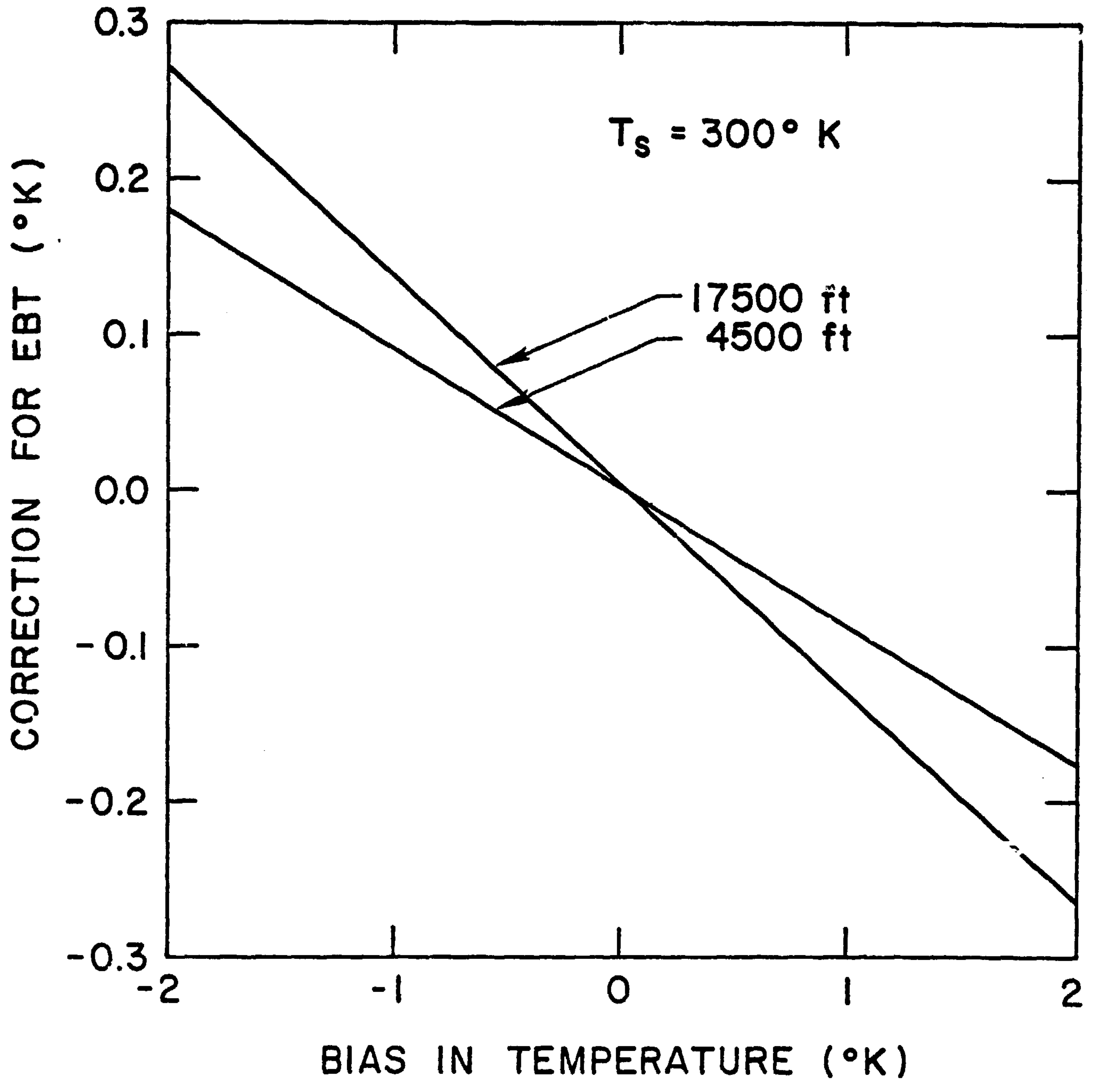

Fig. 4.9 Variation of correction with bias in atmospheric temperature profile for two altitudes and T_s = 300°K.

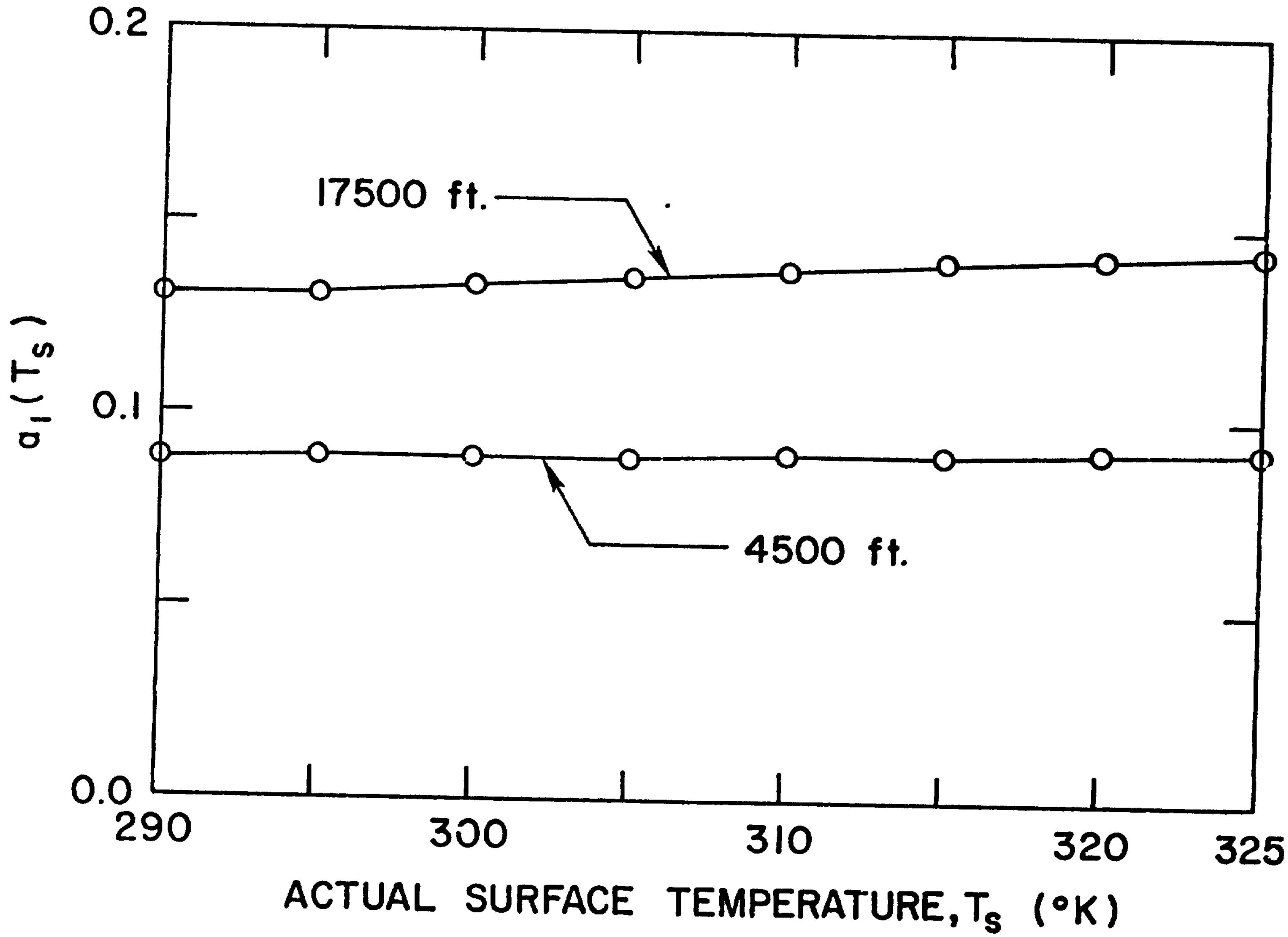

Fig. 4.10 Variation of regression coefficient a_1 with actual surface temperature for two altitudes.

Table 4.10

Regression coefficient a_1 as a function of actual surface temperature and altitude for the temperature profile variation study.

Altitude (ft)	Regression Coefficients								
	290°K	295°K	300°K	305°K	310°K	315°K	320°K	325°K	Average
500	0.017	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.016
1500	0.042	0.042	0.041	0.041	0.041	0.041	0.040	0.040	0.041
2500	0.062	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061
4500	0.088	0.088	0.089	0.089	0.090	0.090	0.091	0.092	0.090
6500	0.106	0.107	0.107	0.107	0.109	0.110	0.111	0.113	0.109
8500	0.117	0.118	0.118	0.120	0.122	0.123	0.125	0.126	0.121
10500	0.123	0.125	0.125	0.127	0.129	0.130	0.132	0.134	0.128
12500	0.127	0.128	0.129	0.132	0.134	0.135	0.137	0.139	0.133
14500	0.129	0.131	0.132	0.134	0.136	0.138	0.140	0.142	0.135
17500	0.131	0.131	0.134	0.135	0.137	0.140	0.142	0.144	0.137

Table 4.10 that the temperature dependence of the coefficient a_1 in this case is very weak. Average values of a_1 (over all values of T_s) are obtained for each altitude. These are listed in the last column of Table 4.10 and shown in Figure 4.11. The figure shows a_1 as a strong function of altitude.

The total correction in this case also consists of an additional component due to water vapor and can be expressed as

$$\Delta T = \Delta T_t + \Delta T_w \tag{4.2}$$

where ΔT_t is computed from the coefficients given in Table 4.10 and ΔT_w corresponds to the presence of standard water vapor burden.

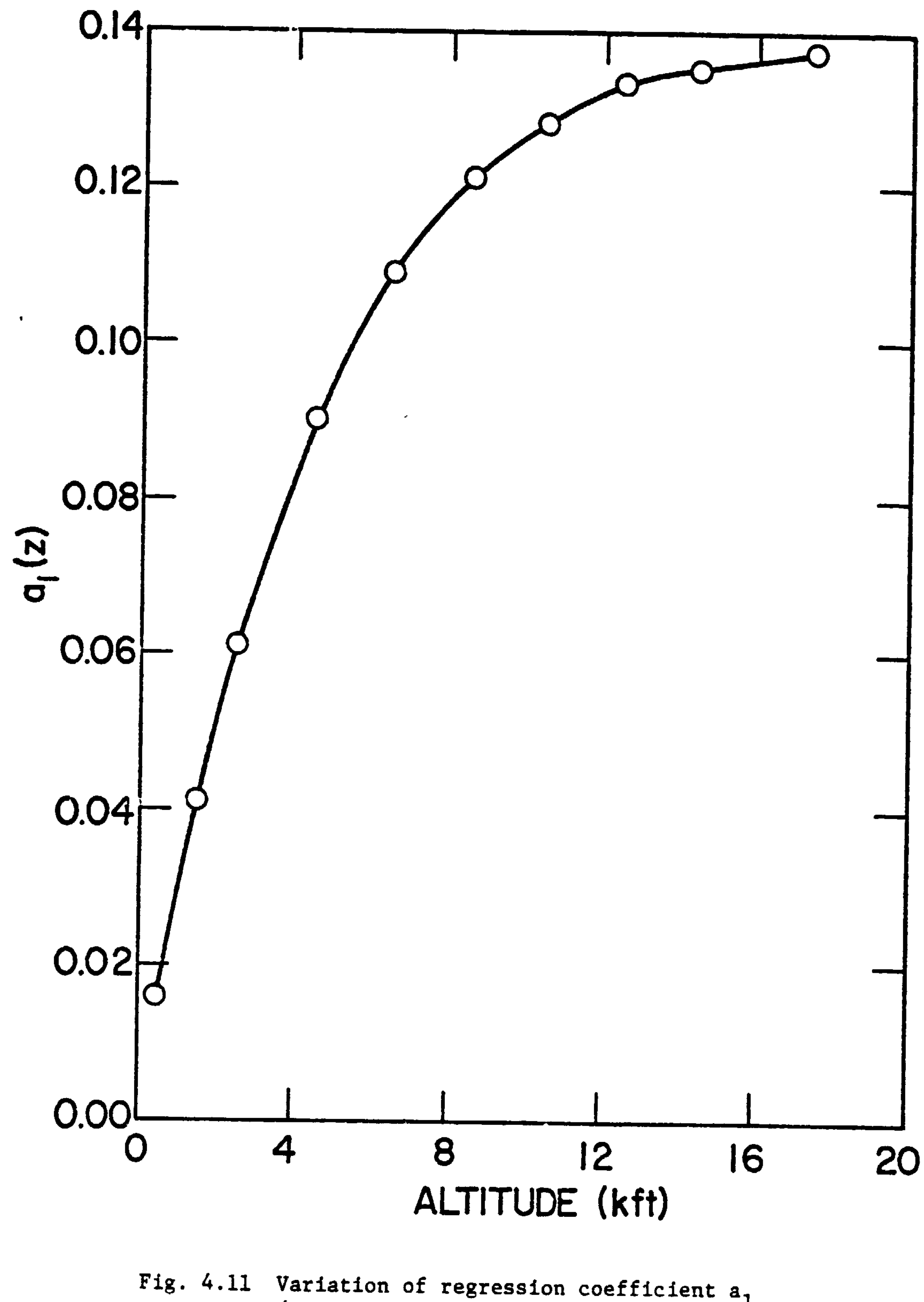

Fig. 4.11 Variation of regression coefficient a_1 (averaged over T_s) with altitude.

5. MODEL CALCULATIONS FOR TWO PARAMETERS

Deviation of only one parameter from its initial value, as considered in the previous section, represents a highly idealized situation for the real atmosphere where more than one parameter may undergo deviations at the same time. In this study we have examined some cases where two of the input parameters undergo deviations simultaneously. It is evident from the discussion in Section 4 that the important parameters affecting the effective brightness temperature are: surface emittance, water vapor burden, and the atmospheric temperature profile. Several combinations of these parameters have been examined in this section. It is intended to establish relationships between the combined correction ΔT_c and the individual corrections ΔT_x caused by separate variations of the two parameters.

5.1 Surface Emittance - Temperature Profile Variations

Extensive model calculations were made to examine the relationships between the individual and combined corrections in this case. Computations were made for five values of surface emittance, namely, 1.00, 0.95, 0.90, 0.85, and 0.80 and five atmospheric temperature profiles. These temperature profiles were characterized by fixed biases of +2°K, +1°K, -1°K and -2°K in addition to the standard profile as given in Table 3.1. Computations were made for all eight values of T_s and calculations for an altitude of 17,500 ft. and $T_s = 325°K$ are presented in Table 5.1. This particular set of parameters has been chosen for illustration to observe the largest differences between the sum of the individual corrections ($\Sigma\ \Delta T_x$) and the combined correction ΔT_c. The first column of the table lists the values of surface emittance and the deviation of emittance from the initial value of unity. The next five columns list the values of the EBT and the differences ($\Sigma\ \Delta T_x - \Delta T_c$) for the various temperature profiles. It can be seen from this table that the largest difference is 0.016°K

<u>Table 5.1</u>

Simultaneous Variation of Parameters
Surface Emittance - Temperature Profile
Alt. = 17,500 ft.; T_s = 325°K

Emittance/ Deviation	T' = T-2	T' = T-1	T' = T	T' = T+1	T' = T+2
1.00	319.405	319.555	319.700	319.842	319.981
0.00	0.000	0.000	0.000	0.000	0.000
0.95	315.714	315.862	316.006	316.146	316.282
-0.05	-0.003	-0.001	0.000	0.002	0.005
0.90	311.926	312.072	312.214	312.352	312.487
-0.10	-0.007	-0.003	0.000	0.004	0.008
0.85	308.030	308.173	308.313	308.450	308.583
-0.15	-0.012	-0.005	0.000	0.005	0.011
0.80	304.021	304.162	304.300	304.435	304.567
-0.20	-0.016	-0.007	0.000	0.007	0.014

which is much smaller than the acceptable 0.1°K. It can be inferred from these results that the combined correction in this case may be represented as the algebraic sum of the individual corrections. Again, because of the presence of the standard burden of water vapor in the atmosphere in this case (without which the variations of temperature profile will be meaningless), it becomes essentially a three-parameter case. The total correction may be expressed mathematically as

$$\Delta T_c = \Delta T_x + \Delta T_y + \Delta T_w \tag{5.1}$$

where ΔT_w represents the correction due to standard water vapor burden and ΔT_x & ΔT_y represent corrections due to the deviations of the other two parameters. Also, it is important to note that correction ΔT_x due deviation of emittance has to be calculated using regression coefficients obtained for the wet atmosphere (Table 4.4).

The behavior of the corrections outlined above may be understood qualitatively in physical terms as follows: the decrease of surface emittance lowers surface radiance while the change in the atmospheric temperature profile affects the atmospheric radiance completely independently. The change in absorption of the surface radiation by atmospheric constituents under the modified temperature profile has very small effect on the total upwelling radiance and hence on the effective brightness temperature.

5.2 Surface Emittance - Water Vapor Burden Variations

Model calculations in this case were performed for the same five values of surface emittance as in subsection 5.1 and water vapor burdens of 0.0, 0.5, 1.0 and 2.0. Results of this calculation for the altitude of 17,500 ft. and T_s = 325°K were chosen again for illustration and are presented in Table 5.2. The first column of this table lists the water vapor burden and the next five columns list the EBT and the differences ($\Sigma\ \Delta T_x - \Delta T_c$) for the

Table 5.2

Simultaneous Variation of Parameters
Surface Emittance - Water Vapor Burden
Altitude = 17,500 ft.; T_s = 325°K

H_2O Burden	ε / Δε	Effective Brightness Temperature (°K)			
	1.00 0.00	0.95 -0.05	0.90 -0.10	0.85 -0.15	0.80 -0.20
0.0	325.000 0.000 –	320.881 0.000 –	316.646 0.000 –	312.283 0.000 –	307.777 0.000 –
0.5	322.748 0.000 –	318.806 -0.177 0.0191	314.758 -0.364 0.0194	310.592 -0.561 0.0196	306.297 -0.772 0.0199
1.0	319.700 0.000 –	316.006 -0.425 0.0195	312.214 -0.868 0.0196	308.313 -1.330 0.0197	304.300 -1.823 0.0200
2.0	310.875 0.000 –	307.898 -1.142 0.0196	304.857 -2.336 0.0198	301.744 -3.586 0.0200	298.550 -4.898 0.0201

various values of surface emittance. It is clear from Table 5.2 that the combined correction in this case cannot be represented by algebraic sum of the individual corrections as in equation (5.1). Several analytical forms were tried for representing the combined corrections in this case and it was found after considerable numerical experimentation that it can be represented as

$$\Delta T_c = \Delta T_x + \Delta T_y + k_1 \cdot \Delta T_x \cdot \Delta T_y \tag{5.2}$$

the last term on the right-hand side representing the difference or residual correction. Values of the coefficient k_1 obtained for the various combinations of parameters involved in Table 5.2 are listed just below the residual corrections. The blank spaces appear at those locations where the residual correction as well as the individual correction due to one of the parameters are both zero. For these cases, the coefficient k_1 is mathematically indeterminate although practically zero. It can be seen from Table 5.2 that the value of k_1 for this set is approximately constant. A mean value of 0.0197 ± 0.003 was obtained for this set. Similar mean values were obtained for all eight values of T_s and all ten altitudes, and are presented in Table 5.3. Figure 5.1 shows k_1 as a function of T_s for $z = 17{,}500$ ft. (circles and solid lines) and also as a function of altitude for $T_s = 300°K$ (squares and dashed lines). Value of k_1 for any values of the parameters other than those listed in Table 5.3 may be obtained by linear interpolation.

It is important to note here that because water vapor burden is itself an independent variable in this case and individual correction due to water vapor, ΔT_y is calculated separately, the emittance correction, ΔT_x in this case has to be computed using regression coefficients obtained for the dry atmosphere (Table 4.2).

<u>Table 5.3</u>

Coefficient k_1 representing residual correction for Surface Emittance - Water Vapor Burden variations.

Altitude (ft)	Actual Surface Temperature (°K)							
	290	295	300	305	310	315	320	325
500	0.4510	0.1420	0.0824	0.0575	0.0439	0.0356	0.0296	0.0252
1500	0.3130	0.1230	0.0758	0.0541	0.0418	0.0341	0.0286	0.0245
2500	0.2400	0.1100	0.0702	0.0511	0.0401	0.0328	0.0277	0.0238
4500	0.1690	0.0913	0.0619	0.0464	0.0370	0.0306	0.0261	0.0227
6500	0.1330	0.0794	0.0560	0.0430	0.0346	0.0290	0.0249	0.0218
8500	0.1130	0.0716	0.0519	0.0404	0.0329	0.0278	0.0240	0.0211
10500	0.1010	0.0665	0.0490	0.0386	0.0318	0.0270	0.0234	0.0206
12500	0.0939	0.0631	0.0470	0.0374	0.0309	0.0263	0.0229	0.0202
14500	0.0889	0.0607	0.0456	0.0364	0.0303	0.0259	0.0225	0.0200
17500	0.0845	0.0586	0.0444	0.0356	0.0297	0.0255	0.0222	0.0197

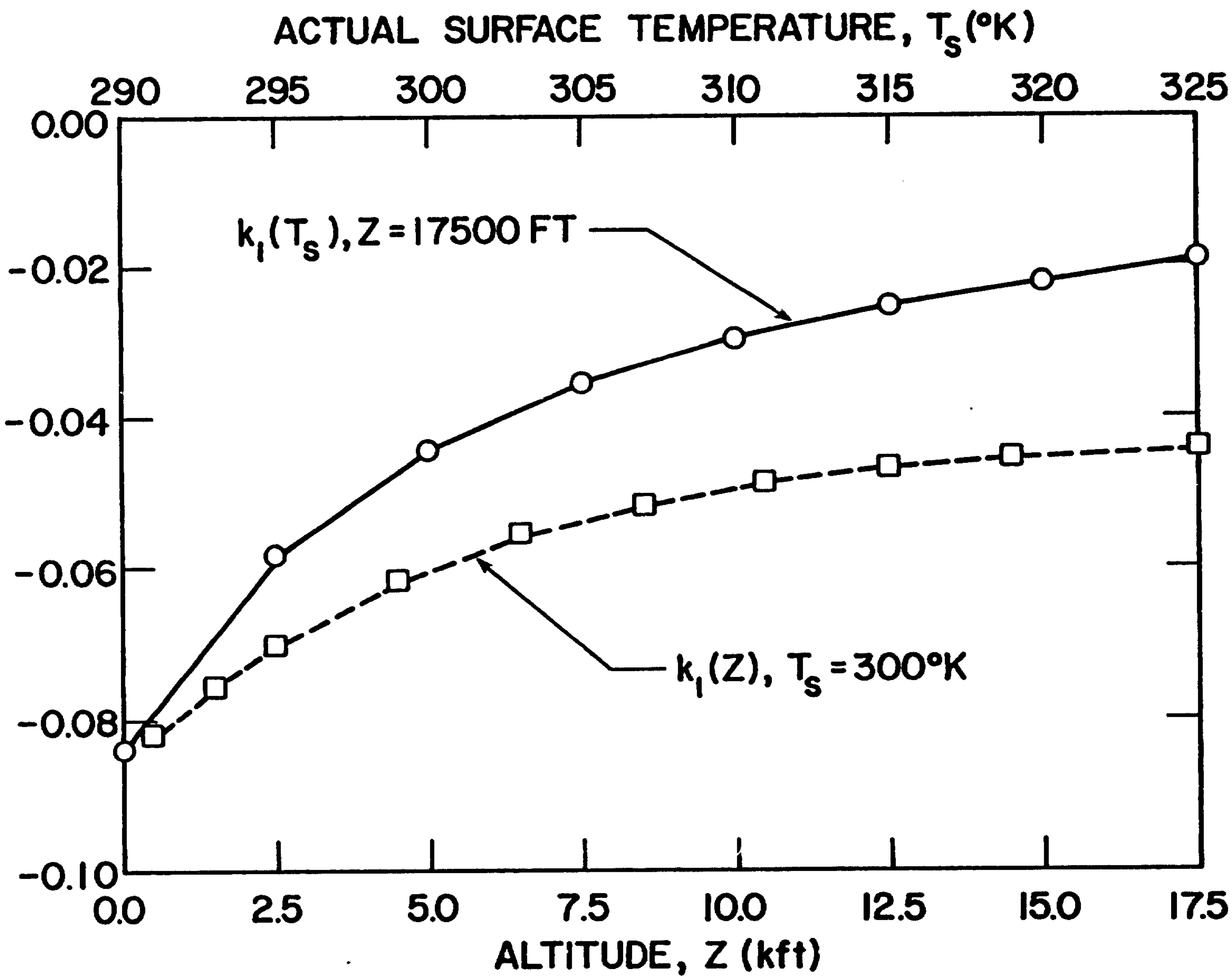

Fig. 5.1 Variation of coefficient k_1 with actual surface temperature (solid curve) and with altitude (dashed curve).

The observed differences or residual corrections in this case may be understood qualitatively in the following way. The atmosphere being cooler than the surface for the cases considered, its effect is to attenuate the surface radiation. Since a decrease of surface emittance decreases the input surface radiance to the atmosphere, the net attenuation will be smaller in the latter case. This in effect is responsible for the over-prediction of correction observed in Table 5.2 when both deviations are considered separately.

5.3 Water Vapor Burden - Temperature Profile Variations

Model calculations in this case were carried out for the five temperature profiles mentioned in subsection 5.1 and three values of water vapor burden, namely 0.5, 1.0 and 2.0. Zero water vapor burden was not considered in this case again, because temperature profile variations lose meaning in absence of any water vapor. Results obtained for the altitude of 17,500 ft. and $T_s = 325°K$ are presented in Table 5.4 as an illustration, though they were obtained for all eight values of T_s and all ten altitudes. The first column of the table lists the water vapor burden (and the deviation of the water vapor burden relative to the standard as explained later). The next five columns list the EBT values obtained for the various temperature profiles as indicated. It can be seen from Table 5.4 that for this case also the combined correction cannot be represented by the algebraic sum of the individual co-rections. The numbers entered below the EBT values are the residual corrections or the differences $(\Sigma \Delta T_x - \Delta T_c)$. These differences are zero for $T' = T$ because this represents essentially a one-parameter situation. The differences also equal zero for the standard water vapor burden because the one-parameter temperature profile variation calculations (subsection 4.3) were made in the presence of standard water vapor burden. Again, because the temperature profile variations become meaningless without water vapor, standard water vapor burden is considered as one of the new initial conditions in this case. The numbers entered below the water vapor burden values in the first column represent the deviations of water vapor burden relative to the new initial value.

Several analytical representations were tried and it was found that the total correction for this set of parameters may be represented as

$$\Delta T_c = \Delta T_x + \Delta T_y + k_2 \cdot \Delta T'_x \cdot \Delta T_y \tag{5.3}$$

where ΔT_x and ΔT_y represent the individual corrections due to water vapor burden and temperature profile deviations respectively. The last term again, represents the residual correction and $\Delta T'_x$ is defined as

$$\Delta T'_x = \Delta T_w - \Delta T_x \tag{5.4}$$

where ΔT_w represents the magnitude of correction due to standard water vapor burden. The values of the coefficient k_2 for the cases covered in Table 5.4 are entered just below the residual corrections in the same table. Blank spaces occur at those places in this table where the residual correction and one of the individual corrections are both zero and, therefore, k_2 is again mathematically indeterminate though practically zero. Table 5.4 also shows that k_2 values for $\Delta x = 2.0$ (third row) are slightly higher than those for $\Delta x = 0.5$ (first row) while within each group the spread is very small. An average value of $k_2 = 0.249 \pm 0.014$ was obtained for this set and it was determined that the maximum error introduced in the computation of ΔT_c using this average would still be much smaller than 0.1°K. Similar average values of k_2 were obtained for all eight values of T_s and all ten altitudes and the results are presented in Table 5.5.

The magnitudes of the residual corrections as shown in Table 5.4 can also be explained qualitatively in terms of changes in attenuation of surface

Table 5.4

Simultaneous Variation of Parameters
Water Vapor Burden - Temperature Profile
Alt. = 17,500 ft.; T_s = 325°K

Water Vapor Burden	Atmospheric Temperature Profile				
	T' = T-2	T' = T-1	T' = T	T' = T+1	T' = T+2
0.5	322.666	322.707	322.748	322.788	322.827
(-0.5)	-0.213	-0.104	0.000	0.102	0.202
	0.237	0.235	–	0.236	0.236
1.0	319.405	319.555	319.700	319.842	319.981
(0.0)	0.000	0.000	0.000	0.000	0.000
	–	–	–	–	–
2.0	309.893	310.391	310.875	311.345	311.801
(1.0)	0.687	0.339	0.000	-0.328	-0.645
	0.264	0.265	–	0.262	0.260

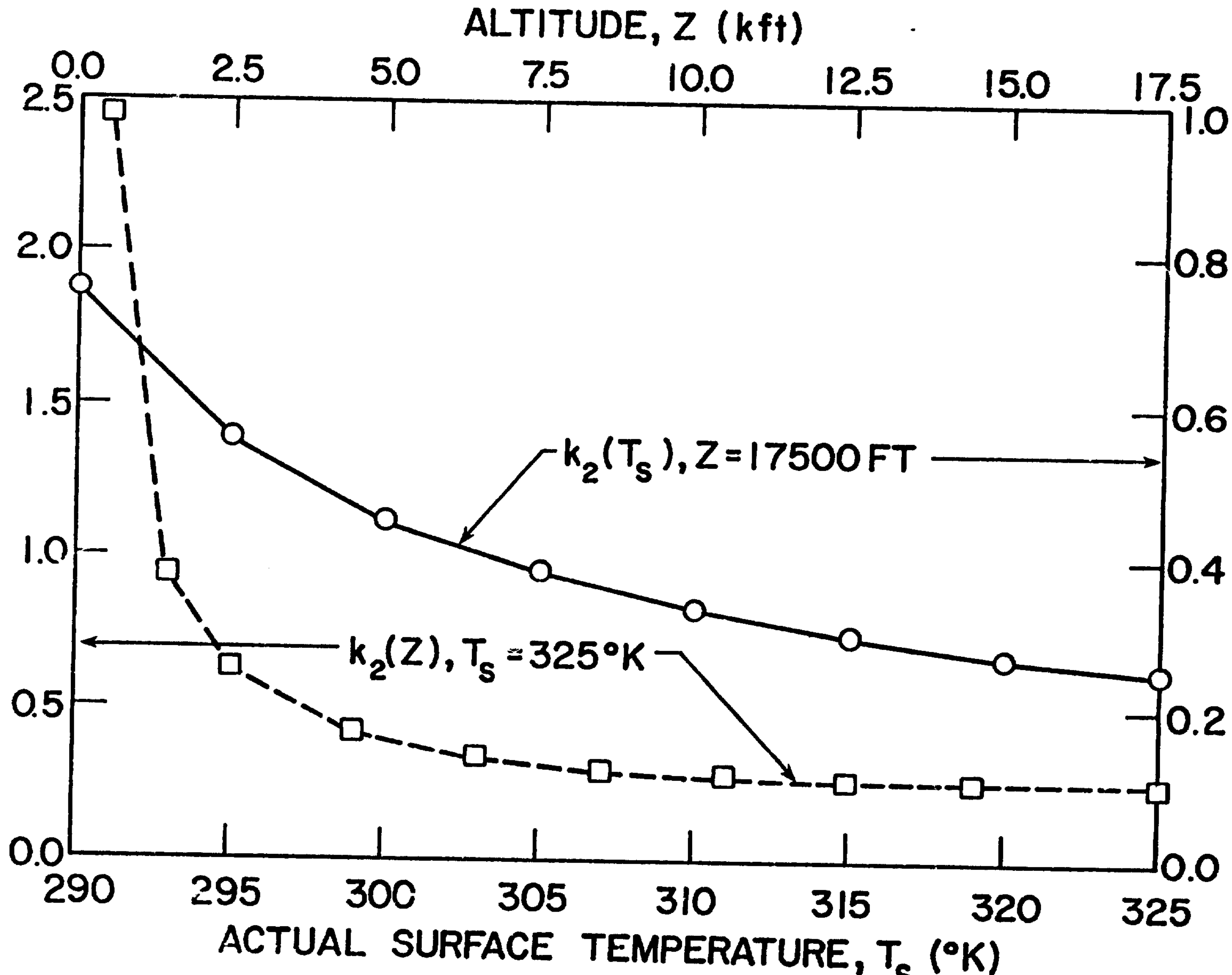

Fig. 5.2 Variation of coefficient k_2 with actual surface temperature (solid curve) and with altitude (dashed curve).

Table 5.5

Coefficient k_2 representing residual correction for Water Vapor Burden - Temperature Profile variations.

Altitude (ft)	Actual Surface Temperature (°K)							
	290	295	300	305	310	315	320	325
500	25.260	8.794	5.540	4.167	3.489	2.960	2.664	2.442
1500	7.319	3.122	2.079	1.597	1.320	1.142	1.028	0.9353
2500	3.912	1.947	1.336	1.049	0.8743	0.7642	0.6832	0.6226
4500	1.988	1.159	0.8461	0.6782	0.5753	0.5056	0.4522	0.4124
6500	1.343	0.8648	0.6529	0.5368	0.4552	0.4030	0.3626	0.3322
8500	1.063	0.7208	0.5587	0.4606	0.3987	0.3533	0.3190	0.2924
10500	0.9199	0.6448	0.5098	0.4232	0.3680	0.3278	0.2963	0.2722
12500	0.8383	0.6002	0.4785	0.4018	0.3499	0.3126	0.2827	0.2588
14500	0.7886	0.5774	0.4596	0.3983	0.3397	0.3042	0.2757	0.2541
17500	0.7510	0.5547	0.4454	0.3795	0.3321	0.2970	0.2707	0.2493

radiation caused by changed water vapor burden and due to changes in emission from atmospheric water vapor because of the bias in the atmospheric temperature profile.

6. APPLICATION OF ALGORITHM

The information and algorithm developed in Sections 2, 4 and 5 can now be used to determine the correction to the measured effective brightness temperature for a known set of surface and atmospheric parameters. It can be evaluated using appropriate forms of equations (2.5) for one-parameter cases or (2.5) and (2.6) for more than one parameters. Various explicit forms of equation (2.5) were developed for specific cases as (4.1) and (4.2) and equation (2.6) as (5.1), (5.2) and (5.3). The regression coefficients required for these computations were determined and tabulated in Sections 4 and 5.

6.1 Evaluation of Correction

It is evident from Tables 4.2, 4.4, 4.6 and 4.10 that the regression coefficients a_n determined for various cases are dependent on the altitude as well as the actual surface temperature. Coefficients k_1 and k_2 which are used in evaluation of the residual correction, listed in Tables 5.3 and 5.5, also exhibit similar characteristics. Figures 4.5, 4.8, 4.11, 5.1 and 5.2 show that all regression coefficients for any altitude between 500 and 17,500 ft. can be obtained with desired accuracy by linear interpolation from the tabulated values. Since the actual surface temperature, T_s is the desired end result of the entire computation, an iterative procedure has to be developed to arrive at its appropriate value.

Values of the regression coefficients a_n as well as k_1 and k_2 for the appropriate altitude referring to $T_s = 300°K$ are chosen as their initial estimates. Correction is computed using appropriate forms of equations (2.5) and (2.6). This correction combined with the measured value of EBT yields the first estimate of the actual surface temperature, say T_{s_1}. Values of the temperature-dependent coefficients a_n as well as k_1 and k_2 are now obtained corresponding to T_{s_1}. It was not found possible to represent the temperature-dependence of each of these coefficients by analytical relations and, therefore, it was decided to obtain the coefficients corresponding to T_{s_1} by linear interpolation between tabulated values. Correction is evaluated again using these coefficients and equations (2.5) and (2.6). The second estimate of actual surface temperature, T_{s_2} is obtained by combining this latter correction with the measured EBT. This iterative process is continued till successive estimates of T_s become consistent within 0.01°K.

A computer program named CORRECT has been developed to accomplish the evaluation of correction using the above procedure. The program generates a table of regression coefficients for the altitude under consideration using interpolation, if necessary. A set of five parameters, namely, EBT (effective brightness temperature), ALT (altitude), EMI (surface emittance), DW (water vapor burden) and DT (temperature profile bias) is supplied to this program. Depending upon the values of the last three parameters, the program decides if it is a one- or two-parameter case and automatically selects the appropriate equations for evaluating the correction. The program performs up to a maximum of ten iterxations and if the T_s value does not converge as desired, it reports the last estimate of T_s and indicates the nonconvergence. A listing of this program is also reproduced in Appendix B.

6.2 Sample Calculations

Extensive sample calculations were made to check out the working of program CORRECT using the EBT values obtained for various sets of parameters from the program PRTFIVE. Table 6.1 shows a set of such results covering a wide range of surface temperatures and other parameters. The first column of this table lists the values of the actual surface temperature (TEMS) used in the program PRTFIVE to obtaine EBT. The last column lists the values of the retrieved surface temperature (SURTEMP) obtained by the program CORRECT.

The other symbols used in this table have been explained earlier. The sets of parameters chosen for these calculations were intended to cover all possible combinations and also to show largest possible differences between the actual and retrieved surface temperatures. It is important to note that the combinations (i) surface emittance - water vapor burden, and (ii) water vapor burden-temperature profile (subsections 5.2 and 5.3) which involve the computation of residual correction are likely to exhibit larger differences. A comparison of TEMS and SURTEMP values in this table shows that the largest difference is only 0.14°K.

Table 6.1

Results of sample calculations made with program CORRECT.

TEMS(°K)	EBT(°K)	ALT(FT)	EMI	DW	DT(°K)	SURTEMP(°K)
325	307.78	10500	0.80	0.00	0.00	325.00
315	296.48	12500	0.80	1.00	0.00	314.99
310	297.33	6500	1.00	3.00	0.00	309.97
295	293.21	8500	1.00	1.00	-2.00	295.00
320	315.60	14500	1.00	1.00	+2.00	319.99
305	288.02	17500	0.80	1.00	-2.00	305.00
310	292.53	17500	0.80	1.00	+2.00	309.97
300	282.88	17500	0.80	2.00	0.00	300.10
295	294.00	17500	1.00	0.50	-2.00	294.94
315	304.51	17500	1.00	2.00	+2.00	314.86
320	295.36	17500	0.80	2.00	0.00	320.04
315	312.26	17500	1.00	0.50	+2.00	314.92

7. SENSITIVITY CALCULATIONS

It is important in a study of this type to examine the sensitivity of the retrieved surface temperature to the uncertainties in the various input parameters. It is possible in cases of certain parameters to estimate the sensitivity from the information already presented in Section 4. For others, however, separate calculations had to be made for this purpose. Effects of uncertainty in the values of surface emittance, water vapor burden, temperature distribution and altitude of observation are examined in this section.

7.1 Surface Emittance

Sensitivity of the retrieved surface temperature to uncertainties in assumed value of surface emittance may be estimated from the results presented in Tables 4.1 and 4.3 for dry and wet atmosphere conditions, respectively. These tables list the values of EBT as a function of T_s for several values of surface emittance. Differences between EBT values referring to $\varepsilon = 1.00$ and 0.95 are indicative of the differences between the measured values of EBT expected as a result of a five percent variation of surface emittance. Since surface temperature is obtained directly from the EBT, it is reasonable to assume that these differences are approximately equal to the errors introduced in the retrieved surface temperature due to five percent uncertainty in the assumed value of surface emittance.

Figure 7.1 shows EBT as a function of the actual surface temperature obtained with two values of input emittance (1.00 and 0.95). The dry atmosphere results are independent of altitude and the wet atmosphere results refer to the altitude of 17,500 ft. It is evident from figure 7.1 that for both cases (dry and wet) the differences between the two EBT curves are

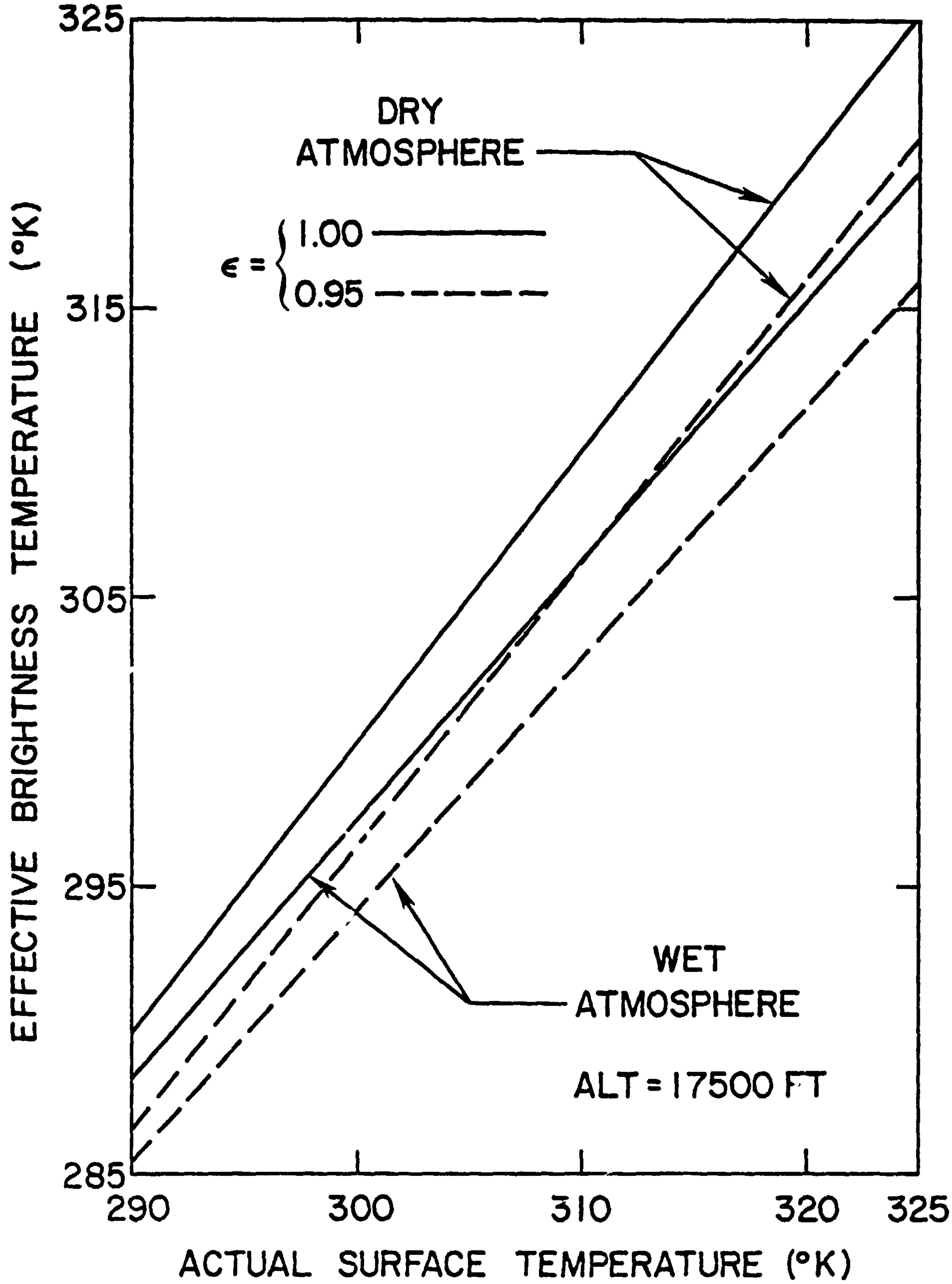

Fig. 7.1 Data showing sensitivity of EBT to uncertainty in the value of surface emittance.

substantial (an average of approx. 3.3°K). It is inferred, therefore, that surface emittance is a very important parameter and great caution should be exercised in assuming its value in the present work.

7.2 Water Vapor Burden

Sensitivity of the retrieved surface temperature to uncertainties in the assumed water vapor burden has been estimated by computing EBT for water vapor burdens of 0.75 and 1.25 and comparing the results with EBT values obtained for standard water vapor burden. Table 7.1 shows results for all eight values of T_s and the altitude of 17,500 ft. The results presented in this table are depicted in Figure 7.2 and show that a 25 percent variation of water vapor burden affects the measured EBT from 0.5 to 1.5°K (average of about 1°K) for the range of T_s covered in the present work. It is easy to visualize that the values of surface temperature obtained from these values of EBT will differ by an average of approximately 1°K. It can be inferred, therefore, that an uncertainty of 25 percent in the waver vapor burden introduces an error of approximately 1°K in the retrieved surface temperature.

7.3 Atmospheric Temperature Distribution

It can be seen from Table 4.9 that a constant bias of 2°K on the atmospheric temperature profile affects the EBT measured from 17,500 ft. by an average of approximately 0.27°K for the range of T_s under consideration. As discussed in the previous subsections, it can be inferred from these results that an uncertainty of 2°K in the atmospheric temperature distribution throughout the atmosphere introduces an error of approximately 0.27°K in the retrieved surface temperature.

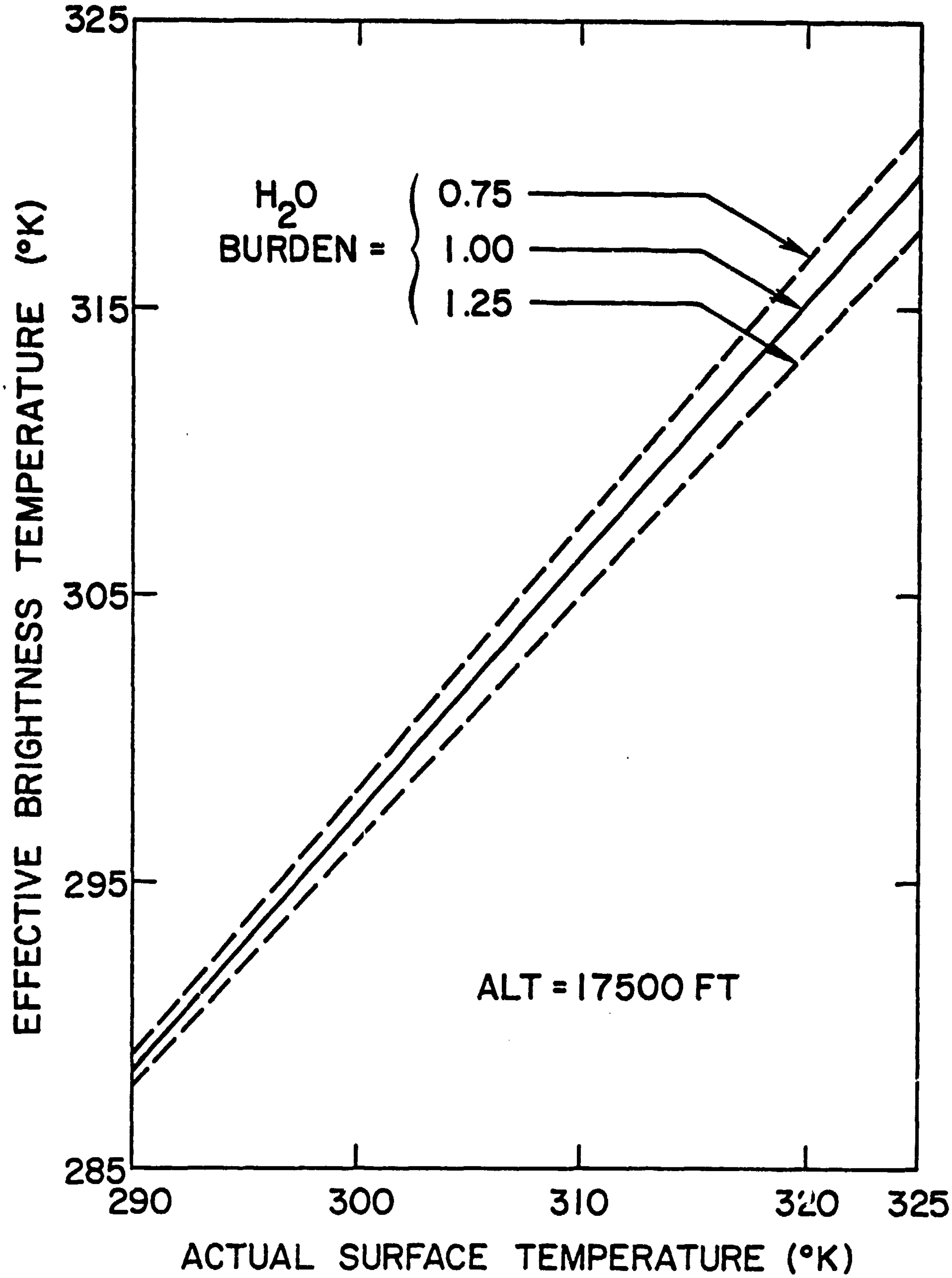

Fig. 7.2 Data showing sensitivity of EBT to uncertainty in water vapor burden.

Table 7.1

Results showing the effect of uncertainty in water vapor burden on effective brightness temperature.

Actual Surface Temp. (°K)	Effective Brightness Temp. (°K)		
	Water Vapor Burden		
	0.75	1.00	1.25
290	288.96	288.50	287.98
295	293.55	292.91	292.18
300	298.16	297.34	296.40
305	302.78	301.79	300.65
310	307.41	306.25	304.91
315	312.05	310.72	309.19
320	316.70	315.21	313.49
325	321.35	319.70	317.80

7.4 Altitude of Observation

The effect of uncertainty in the altitude of observation on retrieved surface temperature is estimated by computing EBT as observed from 17,000 and 18,000 ft. and comparing the results with those obtained for 17,500 ft. The differences observed for both cases were very small ($\leq$0.02°K) and were not considered significant. It was inferred, therefore, that an uncertainty of up to 500 ft. (at an average altitude of 17,500 ft.) in the altitude of observation introduces no significant error in the retrieved surface temperature.

8. CONCLUSIONS

The present study shows that it is possible to determine the atmospheric correction to the effective brightness temperature as measured remotely by a radiation thermometer without having to perform detailed radiative transfer calculations. It is shown from the model calculations in Section 4 that corrections can be represented accurately by simple analytical expressions (linear, quadratic or cubic) in terms of the magnitudes or deviations of the corresponding surface or atmospheric parameters. It is also shown from the model calculations in Section 5 that combined correction for simultaneous variations of several parameters can be represented in terms of their individual corrections. It has been shown further (Section 6) that these simple expressions can be used to compute the corrections with a high degree of accuracy from a knowledge of the magnitudes or deviations of the various surface and atmospheric parameters over wide range conditions. The largest cumulative mathematical error introduced by this algorithm was found to be less than 0.15°K. It can also be seen from the results of the sensitivity calculations presented in Section 7 that uncertainties in the assumed values of surface emittance and water vapor burden introduce large errors in the retrieved surface temperature. Uncertainties in the atmospheric temperature distribution and the altitude of observation are found to have relatively smaller effects. It is estimated that the use of this algorithm instead of the expensive radiative transfer calculations will reduce the time and cost involved in surface temperature retrieval by at least an order of magnitude. Although the results presented here refer to one particular instrument (PRT-5), the technique is general and should be applicable to any radiometric measurement.

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APPENDIX A1

EXPLANATION OF SYMBOLS USED IN

PROGRAM "PRTFIVE" AND ITS SUBROUTINES

A	Constant used in representing frequency variation of the continuum absorption coefficient.
AC	Total monochromatic absorption coefficient.
ACB, ACE & ACM	Wing contribution to the total absorption coefficient at the interval boundaries and center.
AL	Array of half-widths of the individual lines.
ALFT, ALKM	Altitude of observation in feet and kilometers, respectively.
ALX	Width of a narrow sub-interval near line center.
ATR	Integrated upwelling radiance at the altitude of observation including atmospheric attenuation.
B	Another constant used in representing frequency variation of the continuum absorption coefficient.
BETA	Exponent used for the above purpose.
BTR	Integrated upwelling radiance at the altitude of observation excluding atmospheric attenuation.
DEL	Width of an interval.
DLIM	Width of the region from which the direct contribution is obtained.
EL	Array of energies of the lower states for individual lines.
EMI	Surface emittance.
FACT	Factor used for obtaining line-intensities corresponding to the temperature of each layer.
FIL	Array of filter function for all intervals.
FR	Array of frequencies of the individual lines.
FRB	Frequencies at the boundaries of intervals.

FRC	Frequencies at the centers of intervals.
FRE	Frequencies of all lines within one interval.
FRG	Frequencies of all locations where absorption coefficient is calculated within one interval.
FRS	Frequencies at the sub-interval boundaries within one interval.
FRT	Tabulated values of filter function.
IG	Total number of frequency locations at which transmittance calculation is made, within one interval.
LA	Number of layers for a given altitude of observation.
LE	Total number of lines in the entire frequency range.
LLH	Number of different altitudes of observation.
LX	Array of number of layers for different altitudes of observation.
MP	Number of lines within one interval.
NQ	Number of sub-intervals in an interval.
NT	Number of surface temperature values for which calculations are made.
PART	A lumped constant accounting for the variations of vibrational and rotational partition functions.
PL	Monochromatic optical thickness.
PLK	Planck functions for different atmospheric layers.
PNTP	Pressure at NTP (760 mm Hg).
PPL	Pressure path length for each layer.
PREC	Average pressure for each layer.
PSK	Planck functions for different values of surface temperature.
PW	Partial pressure of water vapor for each layer.
PXK	Planck functions for surface for the temperature array TEMX.
QV	Concentration of water vapor in different layers (in ppmV).
RAD	Upwelling radiance in one interval at one particular temperature.

RP	Exponent which accounts for the temperature dependence of the rotational partition function.
SI	Array of intensities for individual lines.
TEMC	Average temperature for each layer.
TEMR	Reference temperature for the water vapor line parameters.
TEMS	Array of surface temperatures for which calculations are made.
TEMX	Array of surface temperatures which are used for interpolation.
TEMY	Computed values of effective brightness temperatures.
THC	Thickness of each layer.
TNTP	Temperature at NTP (273°K).
TR	Monochromatic transmittance at each of the frequencies FRG.
TRA	Averaged transmittance for each interval for different layers.
TRS	Averaged transmittance for each interval in the Subroutine TRANS.
VPF	Factor accounting for the temperature dependence of the vibrational partition function.
WF	Frequencies at which the filter function is tabulated.
WIDF	Factor used to convert line half-widths from reference values to those appropriate for each layer.
WL1, WL2	Weighting factors used in the Gauss-Legendre quadrature formula.
WLIM	Width of the regions from which the wing contribution is obtained.
XL1,XL2	Abscissa values used in the Gauss-Legendre quadrature formula.

APPENDIX A2

EXPLANATION OF SYMBOLS USED IN PROGRAM "CORRECT."

A	Current values of the regression coefficients for the first parameter.
A1, A2, & A3	Regression coefficients for all altitudes, temperatures and parameters.
AA1, AA2, & AA3	Regression coefficients for all altitudes and temperatures for one particular parameter.
AD	Regression coefficients for the dry atmosphere surface emittance variation case.
ALFT	Altitudes at layer boundaries in feet.
ALT	Given altitude of observation.
AR1, AR2, & AR3	Regression coefficients for the given altitude of observation for all temperatures and one parameter.
ASTM	Initial estimate of the surface temperature (300°K in all cases).
ASTN	Current estimate of surface temperature during iteration.
AW, AX, & AY	Regression coefficients for water vapor, first parameter and second parameter, respectively, for the given altitude and all temperatures.
AZ1, AZ2, & AZ3	Regression coefficients for the given altitude, all temperatures and all parameters.
B	Current values of the regression coefficients for the second parameter.
C	Current values of the coefficients for the residual correction terms.
C1, C2	Coefficients for the residual correction terms for all altitudes and temperatures.
CZ1, CZ2	Coefficients for the residual correction terms for the altitude of observation.
DE	Deviation of surface emittance from unity.
DT	Bias in atmospheric temperature profile.

DW	Atmospheric water vapor burden in multiples of standard.
DX, DY	Deviations of the two parameters under consideration.
EBT	Measured effective brightness temperature.
EMI	Surface emittance.
ICON	Convergence parameter.
SURTEMP	Retrieved surface temperature.
TEMS	Array of surface temperatures for which calculations are made.

APPENDIX B1

LISTING OF COMPUTER PROGRAM "PRTFIVE"

AND ITS SUBROUTINES

```
      PROGRAM PRTFIVE(INPUT,OUTPUT,TAPE2)
      INTEGER X,Y,T
      DIMENSION ALFT(10),ALKM(10),THC(10),PREC(10),LX(10),
     /VPF(10),OV(10),PPL(10),FRT(25),WF(25),FGR(24),FIL(120),
     /ATR(8,10),BTR(10),FRE(15),PL(200),PSK(8),PLK(10),PXK(10),
     /TEMS(8),TEMX(10),TRA(11),RAD(8),TEMY(8,10),IER(8,10)
      COMMON/ABSORB/FR(320),SI(320),EL(320),AL(320),FRG(200),
     /AC(200),FRB(121),FRC(120),WIDF(10),FACT(10),PARI(10),
     /TEMC(10),PW(10),DLIM,WLIM,DELA,BETA,TEMR,TO,LE,IG,PI,A,B
      COMMON/TRANE/FRS(51),TR(200),WL1,WL2,NQ,DEL
      READ 10, EMI
      READ 10, FRL,FRU,DEL
      READ 11, LE,NT,JT,LLH
      READ 10, DLIM,WLIM,ALX
      READ 10, PNTP,TNTP,TEMR,TO
      READ 10, RP
      READ 12, A,B,BETA
      READ 13, (ALFT(LL),LL=1,LLH)
      READ 14, (PREC(L),L=1,10)
      READ 10, (TEMC(L),L=1,10)
      READ 10, (TEMS(T),T=1,NT)
      READ 10, (TEMX(J),J=1,JT)
      READ 14, (THC(L),L=1,10)
      READ 15, (FRT(M),M=1,25)
      READ 14, (VPF(L),L=1,10)
      READ 16, XL1,XL2,WL1,WL2
      READ 12, (GV(L),L=1,10)
      READ(2,17) (FR(X),SI(X),EL(X),AL(X),X=1,LE)
   10 FORMAT(10F8.2)
   11 FORMAT(16I5)
   12 FORMAT(5E16.3)
   13 FORMAT(10F8.0)
   14 FORMAT(10F8.4)
   15 FORMAT(10F8.3)
   16 FORMAT(8F10.6)
   17 FORMAT(2(F10.3,E12.4,F10.3,F5.3,3X))
C     DETERMINES THE NUMBER OF LAYERS FOR EACH OF THE
C     SEVERAL ALTITUDES OF OBSERVATIONS
      DO 100 LL=1,LLH
      ALKM(LL)=ALFT(LL)*3.048E-04+0.05
      L=0
      STHC=0.
  101 L=L+1
      STHC=STHC+THC(L)
```

```
      ALR=ALKM(LL)-STHC
      IF (ALR.LT.0) GO TO 100
      LX(LL)=L
      GO TO 101
  100 CONTINUE
C   COMPUTES PARTIAL PRESSURE, PRESSURE PATH LENGTH
C   FOR WATER VAPOR AND SOME OTHER ALTITUDE
C   DEPENDENT PARAMETERS
      PI=3.14159
      AWR=1.6
      CONST=1.E+05*TNTP/PNTP
      DO 102 L=1,10
      PART(L)=VPF(L)*(TEMR/TEMC(L))**RP
      FACT(L)=1.439*(TEMC(L)-TEMR)/(TEMC(L)*TEMR)
      WIDF(L)=(SQRT(TEMR/TEMC(L)))*PREC(L)/PNTP
      PPL(L)=CONST*QV(L)*PREC(L)*THC(L)/TEMC(L)
  102 PW(L)=QV(L)*PREC(L)
C   DIVIDES THE ENTIRE FREQUENCY RANGE INTO NARROW INTERVALS
      DELA=0.5*DEL
      RK=(FRU-FRL)/DEL+0.1
      KR=RK
      FRB(1)=FRL
      DO 103 K=1,KR
      FRC(K)=FRB(K)+DELA
  103 FRB(K+1)=FRB(K)+DEL
C   COMPUTES THE INSTRUMENT FILTER FUNCTION FOR
C   EVERY INTERVAL FROM THE TABULATED VALUES
      WF(1)=FRL
      DO 104 M=1,24
      WF(M+1)=WF(M)+10.
  104 FGR(M)=(FRT(M+1)-FRT(M))/(WF(M+1)-WF(M))
      DO 105 K=1,KR
      M=0
  106 M=M+1
      IF (FRC(K).LT.WF(M)) GO TO 105
      IF (FRC(K).GE.WF(M+1)) GO TO 106
      FIL(K)=FRT(M)+FGR(M)*(FRC(K)-WF(M))
  105 CONTINUE
      ALY=2.*ALX
      CONS=18.*6.625E-07
      CNST=6.625*0.3/1.38
C   INITIALIZES TOTAL UPWELLING RADIANCES FOR DIFFERENT
C   ALTITUDES AND SURFACE TEMPERATURES
      DO 107 LL=1,LLH
```

```
      DO 107 T=1,NT
  107 ATR(T,LL)=0.
      DO 108 J=1,JT
  108 BTR(J)=0.
      Y=0
C     STARTS COMPUTING TRANSMITTANCE AND UPWELLING
C     RADIANCE FOR ONE INTERVAL AT A TIME
      DO 109 K=1,KR
      M=0
C     DETERMINES THE NUMBER OF LINES IN ONE INTERVAL
      MP=M
  111 IF (Y.GE.LE) GO TO 110
      Y=Y+1
      IF (FR(Y).LT.FRB(K)) GO TO 111
      IF (FR(Y).GE.FRB(K+1)) GO TO 112
      M=M+1
      FRE(M)=FR(Y)
      MP=M
      GO TO 111
  112 Y=Y-1
  110 CONTINUE
      N=1
C     DETERMINES THE NUMBER OF SUB-INTERVALS IN ONE INTERVAL
      FRS(N)=FRB(K)
      IF (MP.LE.0) GO TO 113
      DO 114 M=1,MP
      DIF=FRE(M)-FRS(N)
      IF (DIF.LE.ALX) GO TO 115
      IF (DIF.LE.ALY) GO TO 116
      FRS(N+1)=FRE(M)-ALY
      FRS(N+2)=FRE(M)-ALX
      FRS(N+3)=FRE(M)
      N=N+3
      GO TO 117
  116 FRS(N+1)=FRE(M)-ALX
      FRS(N+2)=FRE(M)
      N=N+2
      GO TO 117
  115 FRS(N+1)=FRE(M)
      N=N+1
  117 IF (M.EQ.MP) GO TO 118
      DIF=FRE(M+1)-FRS(N)
      IF (DIF.LE.ALX) GO TO 114
      IF (DIF.GT.ALY) GO TO 119
```

```
      FRS(N+1)=FRE(M)+ALX
      N=N+1
      GO TO 114
  119 FRS(N+1)=FRE(M)+ALX
      FRS(N+2)=FRE(M)+ALY
      N=N+2
  114 CONTINUE
  118 DIF=FRB(K+1)-FRE(M)
      IF (DIF.LE.ALX) GO TO 113
      IF (DIF.LE.ALY) GO TO 120
      FRS(N+1)=FRE(M)+ALX
      FRS(N+2)=FRE(M)+ALY
      FRS(N+3)=FRB(K+1)
      NP=N+3
      GO TO 121
  120 FRS(N+1)=FRE(M)+ALX
      FRS(N+2)=FRB(K+1)
      NP=N+2
      GO TO 121
  113 FRS(N+1)=FRB(K+1)
      NP=N+1
  121 NQ=NP-1
C   DETERMINES THE FREQUENCIES AT ALL GRID POINTS WITHIN ONE INTERVAL
      IG=4*NQ
      DO 122 N=1,NQ
      I=4*(N-1)+1
      VAR=0.5*(FRS(N+1)-FRS(N))
      CON=0.5*(FRS(N+1)+FRS(N))
      FRG(I)=CON-VAR*XL1
      FRG(I+1)=CON-VAR*XL2
      FRG(I+2)=CON+VAR*XL2
  122 FRG(I+3)=CON+VAR*XL1
      PNUM=DEL*CONS*FRC(K)*FRC(K)*FRC(K)*1.E-07
      EEX=CNST*FRC(K)
C   COMPUTES VALUES OF PLANCK FUNCTIONS FOR DIFFERENT VALUES OF
C   SURFACE TEMPERATURE AND DIFFERENT LAYERS OF THE ATMOSPHERE
      DO 123 T=1,NT
  123 PSK(T)=PNUM/(EXP(EEX/TEMS(T))-1.)
      DO 124 L=1,10
  124 PLK(L)=PNUM/(EXP(EEX/TEMC(L))-1.)
      DO 125 J=1,JT
  125 PXK(J)=PNUM/(EXP(EEX/TEMX(J))-1.)
      DO 132 J=1,JT
  132 BTR(J)=BTR(J)+PXK(J)*FIL(K)
```

```
C     STARTS TO WORK FOR EACH ALTITUDE SEPARATELY
      DO 109 LL=1,LLH
      DO 126 I=1,IG
  126 PL(I)=0.
      LA=LX(LL)
      LB=LA+1
      TRA(LB)=1.
C     CONSIDERS EACH LAYER SEPARATELY. CALLS SUBROUTINE
C     COEFF TO EVALUATE ABSORPTION COEFFICIENT AT EACH
C     GRID POINT. THEN COMPUTES THE OPTICAL DEPTH AND
C     MONOCHROMATIC TRANSMITTANCE
      DO 127 M=1,LA
      L=LA+1-M
      CALL COEFF(L,K)
      DO 128 I=1,IG
      PL(I)=PL(I)+AC(I)*PPL(L)
      IF (PL(I).GT.675.) GO TO 129
      TR(I)=EXP(-PL(I))
      GO TO 128
  129 TR(I)=0.
  128 CONTINUE
C     CALLS SUBROUTINE TRANS TO COMPUTE AVERAGE
C     TRANSMITTANCE FOR EACH INTERVAL
      CALL TRANS(TRA(L))
  127 CONTINUE
C     COMPUTES INTEGRATED UPWELLING RADIANCE FOR
C     DIFFERENT ALTITUDES AND SURFACE TEMPERATURES
      COMP=0.
      DO 130 L=1,LA
  130 COMP=COMP+PLK(L)*(TRA(L+1)-TRA(L))
      DO 131 T=1,NT
      RAD(T)=COMP+EMI*PSK(T)*TRA(1)
  131 ATR(T,LL)=ATR(T,LL)+RAD(T)*FIL(K)
  109 CONTINUE
      NMAX=10
      NN=10
      NTAB=1
      IOR=2
C     USES THE INTERPOLATION ROUTINE IUNI TO EVALUATE
C     THE EFFECTIVE BRIGHTNESS TEMPERATURE
      DO 133 LL=1,LLH
      DO 133 T=1,NT
      XO=ATR(T,LL)
      IPT=-1
```

```
      CALL  IUNI(NMAX,NN,BTR,NTAB,TEMX,IOR,XO,YO,IPT,IERR)
      TEMY(T,LL)=YO
      IER(T,LL)=IERR
  133 CONTINUE
      DO 134 LL=1,LLH
      PRINT 60,(TEMS(T),ATR(T,LL),TEMY(T,LL),IER(T,LL),T=1,NT)
  134 CONTINUE
      PRINT 61, (TEMX(J),BTR(J),J=1,JT)
   60 FORMAT(1H1////(F15.2,E20.5,F15.3,I10,//))
   61 FORMAT(1H1////(F15.2,E20.5,//))
      STOP
      END
```

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```
      SUBROUTINE COEFF(L,K)
      INTEGER X
      DIMENSION CONT(200)
      COMMON/ABSORB/FR(320),SI(320),EL(320),AL(320),FRG(200),
     /AC(200),FRB(121),FRC(120),WIDF(10),FACT(10),PART(10),
     /TEMC(10),PW(10),DLIM,WLIM,DELA,BETA,TEMR,TO,LE,IG,PI,A,B
C    INITIALIZES ALL ABSORPTION COEFFICIENTS TO ZERO
      ACB=ACM=ACE=0.
      DO 300 I=1,IG
  300 AC(I)=0.
C    STARTS TO GO THROUGH THE LINES TO DETERMINE WHICH
C    ONES CONTRIBUTE FOR THE PARTICULAR INTERVAL
      DO 301 X=1,LE
      DIF=ABS(FR(X)-FRC(K))
      IF (DIF.GT.WLIM) GO TO 301
      SIA=SI(X)*PART(L)*EXP(EL(X)*FACT(L))
      ALB=AL(X)*WIDF(L)
      IF (DIF.GT.DLIM) GO TO 302
C    COMPUTES THE DIRECT CONTRIBUTION
      DO 303 I=1,IG
      FD=FR(X)-FRG(I)
      DEN=PI*(FD*FD+ALB*ALB)
  303 AC(I)=AC(I)+SIA*ALB/DEN
      GO TO 301
C    EVALUATES THE WING CONTRIBUTION AND ADDS
C    THE DIRECT AND WING CONTRIBUTIONS
  302 FB=FR(X)-FRB(K)
      FM=FR(X)-FRC(K)
      FE=FR(X)-FRB(K+1)
      PNUM=SIA*ALB
      ACB=ACB+PNUM/(PI*FB*FB)
      ACM=ACM+PNUM/(PI*FM*FM)
      ACE=ACE+PNUM/(PI*FE*FE)
  301 CONTINUE
      SL1=(ACM-ACB)/(FRC(K)-FRB(K))
      SL2=(ACE-ACM)/(FRB(K+1)-FRC(K))
      DO 304 I=1,IG
      DIF=(FRG(I)-FRB(K))
      IF (DIF.GE.DELA) GO TO 305
      AC(I)=AC(I)+ACB+SL1*DIF
      GO TO 304
  305 AC(I)=AC(I)+ACM+SL2*(DIF-DELA)
  304 CONTINUE
C    COMPUTES THE CONTINUUM PART OF THE ABSORPTION COEFFICIENT
```

```
C    AND ADDS TO THE LINE PART TO EVALUATE THE TOTAL
      FAC=EXP(TO*(TEMR-TEMC(L))/(TEMC(L)*TEMR))*PW(L)
      DO 306 I=1,IG
      CONT(I)=(A+B*EXP(-BETA*FRG(I)))*FAC*2.69E+19
  306 AC(I)=AC(I)+CONT(I)
      RETURN
      END
```

```
      SUBROUTINE TRANS(TRS)
      COMMON/TRANE/FRS(51),TR(200),WL1,WL2,NQ,DEL
C    EVALUATES THE AVERAGE TRANSMITTANCE FOR EACH
C    SUB-INTERVAL USING FOUR-POINT GAUSS-LEGENDRE
C    QUADRATURE FORMULA AND THEN COMPUTES THE
C    AVERAGE TRANSMITTANCE FOR THE ENTIRE INTERVAL
      TRS=0.
      DO 400 N=1,NQ
      I=4*(N-1)+1
      VAR=0.5*(FRS(N+1)-FRS(N))
      SUM1=TR(I)+TR(I+3)
      SUM2=TR(I+1)+TR(I+2)
      SUM=WL1*SUM1+WL2*SUM2
  400 TRS=TRS+SUM*VAR/DEL
      RETURN
      END
```

APPENDIX B2

LISTING OF COMPUTER PROGRAM "CORRECT"

```
      PROGRAM CORRECT(INPUT,OUTPUT,TAPE2)
      DIMENSION ALFT(10),TEMS(8),A1(10,8,3),A2(10,8,3),
     /A3(10,8,3),C1(10,8),C2(10,8),AZ1(8,3),AZ2(8,3),AZ3(8,3),
     /CZ1(8),CZ2(8),AA1(10,8),AA2(10,8),AA3(10,8),AR1(8),
     /AR2(8),AR3(8),AX(8,3),AY(8,3),AW(8,3),AD(8,3),A(3),
     /B(3),C(3),IERL(3,3),IERC(10),IERX(10),IERY(10),IERW(10)
      DATA ICON,IERC1,IERC2,IERL,ASTM/1,11*9,300./
      DATA IERC,IERX,IERY,IERW/40*9/
      DATA ALFT/500.,1500.,2500.,4500.,
     /6500.,8500.,10500.,12500.,14500.,17500./
      DATA TEMS/290.,295.,300.,
     /305.,310.,315.,320.,325./
      READ(2,10) (((A1(L,J,K),L=1,10),J=1,8),
     /((A2(L,J,K),L=1,10),J=1,8),((A3(L,J,K),L=1,10),J=1,8),K=1,3)
      READ(2,10) ((C1(L,J),L=1,10),J=1,8),((C2(L,J),L=1,10),J=1,8)
      READ(2,11) ((AD(J,N),J=1,8),N=1,3)
      READ 12, EBT,ALT,EMI,DW,DT
   10 FORMAT(10F8.4)
   11 FORMAT(8F8.4)
   12 FORMAT(10F8.2)
      DE=EMI-1.
      IORDER=1
C     DETERMINES IF THE ALTITUDE OF OBSERVATION IS
C     ON ONE OF THE LAYER BOUNDARIES
      DO 100 L=1,10
      ADF=0.02*ALFT(L)
      DIFF=ABS(ALFT(L)-ALT)
      IF(DIFF.GT.ADF) GO TO 100
      GO TO 101
  100 CONTINUE
      GO TO 102
C     IF ON THE LAYER BOUNDARY, USES THE COEFFICIENTS
C     FOR THAT ALTITUDE AS THEY ARE
  101 IL=L
      DO 103 K=1,3
      DO 103 J=1,8
      AZ1(J,K)=A1(IL,J,K)
      AZ2(J,K)=A2(IL,J,K)
      AZ3(J,K)=A3(IL,J,K)
  103 CONTINUE
      DO 104 J=1,8
      CZ1(J)=C1(IL,J)
      CZ2(J)=C2(IL,J)
  104 CONTINUE
```

```
      GO TO 139
  102 NMAX=NN=10
      NTAB=8
C    IF NOT, GENERATES TABLE OF COEFFICIENTS AT THE
C    ALTITUDE OF OBSERVATION BY LINEAR INTERPOLATION
      DO 105 K=1,3
      DO 106 J=1,8
      DO 106 L=1,10
      AA1(L,J)=A1(L,J,K)
      AA2(L,J)=A2(L,J,K)
      AA3(L,J)=A3(L,J,K)
  106 CONTINUE
      IPT1=IPT2=IPT3=-1
      CALL IUNI(NMAX,NN,ALFT,NTAB,
     /AA1,IORDER,ALT,AR1,IPT1,IERR)
      IERL(1,K)=IERR
      CALL IUNI(NMAX,NN,ALFT,NTAB,
     /AA2,IORDER,ALT,AR2,IPT2,IERR)
      IERL(2,K)=IERR
      CALL IUNI(NMAX,NN,ALFT,NTAB,
     /AA3,IORDER,ALT,AR3,IPT3,IERR)
      IERL(3,K)=IERR
      DO 107 J=1,8
      AZ1(J,K)=AR1(J)
      AZ2(J,K)=AR2(J)
  107 AZ3(J,K)=AR3(J)
  105 CONTINUE
      IPT4=IPT5=-1
      CALL IUNI(NMAX,NN,ALFT,NTAB,
     /C1,IORDER,ALT,CZ1,IPT4,IERC1)
      CALL IUNI(NMAX,NN,ALFT,NTAB,
     /C2,IORDER,ALT,CZ2,IPT5,IERC2)
  139 CONTINUE
      NMAX=NN=8
      NTAB=3
C    DETERMINES THE COMBINATION OF PARAMETERS RELEVANT
C    TO THE CASE AND SENDS CONTROL TO APPROPRIATE
C    SEGMENT OF THE PROGRAM
      IF (DE.EQ.0.) GO TO 108
      IF (DW.EQ.0.) GO TO 109
      IF (DT.EQ.0.) GO TO 117
      GO TO 111
  108 IF (DW.EQ.1.) GO TO 140
      IF (DT.EQ.0.) GO TO 128
```

```
      GO TO 116
  140 IF (DT.EQ.0.) GO TO 128
      K=3
      DX=DT
      GO TO 130
  109 CONTINUE
C   COMES HERE IF IT IS AN EMITTANCE VARIATION
C   CASE IN THE DRY ATMOSPHERE
      DO 112 N=1,3
      DO 112 J=1,8
      AX(J,N)=AD(J,N)
  112 CONTINUE
      DO 129 N=1,3
  129 A(N)=AX(3,N)
      IT=0
      DX=DE
  115 IT=IT+1
      IF (IT.GT.10) GO TO 113
      COR=A(1)*DX+A(2)*DX*DX
      ASTN=EBT-COR
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 114
      ASTM=ASTN
      IPT=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AX,IORDER,ASTN,A,IPT,IERR)
      IERX(IT)=IERR
      GO TO 115
C   COMES HERE IF IT IS A WATER VAPOR ONLY CASE
  128 CONTINUE
      K=2
      DO 131 J=1,8
      AX(J,1)=AZ1(J,K)
      AX(J,2)=AZ2(J,K)
      AX(J,3)=AZ3(J,K)
  131 CONTINUE
      DO 132 N=1,3
  132 A(N)=AX(3,N)
      IT=0
      DX=D[illegible]
  133 IT=I[illegible]
      IF [illegible] ) GO TO 113
      COR=[illegible] A(2)*DX*DX+A(3)*DX*DX*DX
      ASTN=E[illegible]T-[illegible]OR
```

```
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 114
      ASTM=ASTN
      IPT=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AX,IORDER,ASTN,A,IPT,IERR)
      IERX(IT)=IERR
      GO TO 133
C     COMES HERE IF IT IS AN EMITTANCE
C     VARIATION CASE IN THE WET ATMOSPHERE
  138 K=1
      DX=DE
C     COMES HERE IF IT IS A TEMPERATURE PROFILE VARIATION
C     CASE IN PRESENCE OF STANDARD WATER VAPOR BURDEN
  130 CONTINUE
      DO 134 J=1,8
      AX(J,1)=AZ1(J,K)
      AX(J,2)=AZ2(J,K)
      AX(J,3)=AZ3(J,K)
      AW(J,1)=AZ1(J,2)
      AW(J,2)=AZ2(J,2)
      AW(J,3)=AZ3(J,2)
  134 CONTINUE
      DO 135 N=1,3
      A(N)=AX(3,N)
  135 C(N)=AW(3,N)
      IT=0
  136 IT=IT+1
      IF (IT.GT.10) GO TO 113
      CORX=A(1)*DX+A(2)*DX*DX
      CORW=C(1)+C(2)+C(3)
      COR=CORX+CORW
      ASTN=EBT-COR
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 114
      ASTM=ASTN
      IPT1=IPT2=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AX,IORDER,ASTN,A,IPT1,IERR)
      IERX(IT)=IERR
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AW,IORDER,ASTN,C,IPT2,IERR)
      IERW(IT)=IERR
      GO TO 136
```

```
C    COMES HERE IF IT IS A SURFACE EMITTANCE -
C    TEMPERATURE PROFILE VARIATION CASE IN THE
C    PRESENCE OF STANDARD WATER VAPOR BURDEN
  111 CONTINUE
      DO 118 J=1,8
      AX(J,1)=AZ1(J,1)
      AX(J,2)=AZ2(J,1)
      AX(J,3)=AZ3(J,1)
      AW(J,1)=AZ1(J,2)
      AW(J,2)=AZ2(J,2)
      AW(J,3)=AZ3(J,2)
      AY(J,1)=AZ1(J,3)
      AY(J,2)=AZ2(J,3)
      AY(J,3)=AZ3(J,3)
  118 CONTINUE
      DO 119 N=1,3
      A(N)=AX(3,N)
      B(N)=AY(3,N)
      C(N)=AW(3,N)
  119 CONTINUE
      IT=0
      DX=DE
      DY=DT
  120 IT=IT+1
      IF (IT.GT.10) GO TO 113
      CORX=A(1)*DX+A(2)*DX*DX
      CORY=B(1)*DY
      CORW=C(1)+C(2)+C(3)
      COR=CORX+CORY+CORW
      ASTN=EBT-COR
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 114
      ASTM=ASTN
      IPT1=IPT2=IPT3=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AX,IORDER,ASTN,A,IPT1,IERR)
      IERX(IT)=IERR
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AY,IORDER,ASTN,B,IPT2,IERR)
      IERY(IT)=IERR
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AW,IORDER,ASTN,C,IPT3,IERR)
      IERW(IT)=IERR
      GO TO 120
```

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```
C    COMES HERE IF IT IS A SURFACE EMITTANCE -
C    WATER VAPOR BURDEN VARIATION CASE BUT GOES TO
C    STATEMENT 138 IF THE WATER VAPOR BURDEN IS STANDARD
 117 CONTINUE
     IF (DW.EQ.1.) GO TO 138
     DO 137 N=1,3
     DO 137 J=1,8
 137 AX(J,N)=AD(J,N)
     DO 121 J=1,8
     AY(J,1)=AZ1(J,2)
     AY(J,2)=AZ2(J,2)
     AY(J,3)=AZ3(J,2)
 121 CONTINUE
     CK=CZ1(3)
     DO 122 N=1,3
     A(N)=AX(3,N)
     B(N)=AY(3,N)
 122 CONTINUE
     IT=0
     DX=DE
     DY=DW
 123 IT=IT+1
     IF (IT.GT.10) GO TO 113
     CORX=A(1)*DX+A(2)*DX*DX
     CORY=B(1)*DY+B(2)*DY*DY+B(3)*DY*DY*DY
     CORZ=CK*CORX*CORY
     COR=CORX+CORY+CORZ
     ASTN=EBT-COR
     DIF = ABS(ASTN-ASTM)
     IF (DIF.LE.0.01) GO TO 114
     ASTM=ASTN
     NTAB=3
     IPT1=IPT2=IPT3=-1
     CALL IUNI(NMAX,NN,TEMS,NTAB,
    /AX,IORDER,ASTN,A,IPT1,IERR)
     IERX(IT)=IERR
     CALL IUNI(NMAX,NN,TEMS,NTAB,
    /AY,IORDER,ASTN,B,IPT2,IERR)
     IERY(IT)=IERR
     NTAB=1
     CALL IUNI(NMAX,NN,TEMS,NTAB,
    /CZ1,IORDER,ASTN,CK,IPT3,IERR)
     IERC(IT)=IERR
     GO TO 123
```

```
C   COMES HER IF IT IS A WATER VAPOR BURDEN -
C   TEMPERATURE PROFILE VARIATION CASE.
  116 CONTINUE
      DO 124 J=1,8
      AX(J,1)=AZ1(J,2)
      AX(J,2)=AZ2(J,2)
      AX(J,3)=AZ3(J,2)
      AY(J,1)=AZ1(J,3)
      AY(J,2)=AZ2(J,3)
      AY(J,3)=AZ3(J,3)
  124 CONTINUE
      CK=CZ2(3)
      DO 125 N=1,3
      A(N)=AX(3,N)
      B(N)=AY(3,N)
  125 CONTINUE
      IT=0
      DX=DW
      DY=DT
  126 IT=IT+1
      IF (IT.GT.10) GO TO 113
      CORX=A(1)*DX+A(2)*DX*DX+A(3)*DX*DX*DX
      CORY=B(1)*DY
      CORW=A(1)+A(2)+A(3)
      CORZ=CK*(CORW-CORX)*CORY
      COR=CORX+CORY+CORZ
      ASTN=EBT-COR
      DIF=ABS(ASTN-ASTM)
      IF (DIF.LE.0.01) GO TO 114
      ASTM=ASTN
      NTAB=3
      IPT1=IPT2=IPT3=-1
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AX,IORDER,ASTN,A,IPT1,IERR)
      IERX(IT)=IERR
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /AY,IORDER,ASTN,B,IPT2,IERR)
      IERY(IT)=IERR
      NTAB=1
      CALL IUNI(NMAX,NN,TEMS,NTAB,
     /CZ2,IORDER,ASTN,CK,IPT3,IERR)
      IERC(IT)=IERR
      GO TO 126
C   RESETS THE CONVERGENCE PARAMETER IF THE RESULT
```

```
C    DID NOT CONVERGE AS DESIRED. AND SETS THE
C    LAST ESTIMATE EQUAL TO SURTEMP
  113 ICON=0
  114 SURTEMP=ASTN
      GO TO 127
  110 SURTEMP=EBT
  127 CONTINUE
      PRINT 60, SURTEMP
      PRINT 62, DIF
      PRINT 63, ICON
      PRINT 64
      PRINT 61, ((IERL(N,K),N=1,3),K=1,3)
      PRINT 61, IERC1,IERC2
      PRINT 61, (IERX(I),I=1,10)
      PRINT 61, (IERY(I),I=1,10)
      PRINT 61, (IERC(I),I=1,10)
      PRINT 61, (IERW(I),I=1,10)
   60 FORMAT(1H1///,15X,* SURFACE TEMPERATURE =*,F8.2)
   62 FORMAT(//,15X,* ITERATION RESIDUAL =*,F8.3)
   63 FORMAT(//,15X,* CONVERGENCE PARAMETER =*,I7)
   61 FORMAT(//,10I7)
   64 FORMAT(///,12X,* ERROR PARAMETERS FOR INTERPOLATION*)
      STOP
      END
```

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OF POOR QUALITY