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COMPENSATION OF ATMOSPHERIC EFFECTS WITH A DUAL-CHANNEL AIRBORNE INFRARED RADIOMETER

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Abstract

The principle of compensation of atmospheric effect with a dual-channel airborne infrared radiometer is described analytically. By adopting this dual-channel method, it is investigated to what extent the atmospheric effect can be compensated without the aid of meteorological data. The results show that we can expect an accuracy of $\pm 0.2°C$ in estimation of sea surface temperature, so far as the measurements are not made at very high altitude.

1. Introduction

The measurements of sea surface temperature using an infrared radiometer installed on artificial satellite and/or aircraft suffer from the absorption and emission of the atmosphere and the non-blackness of the sea surface. Generally, detected temperatures of radiometer show rather lower values than the true temperatures of the sea surface. Recently, Saunders (1967) proposed a method to make corrections for both the non-blackness of the sea surface and the atmospheric effects basing on the double measurements made at a normal and a 60° inclined angle. On the other hand, Anding and Kauth (1970) suggested that these effects can be compensated by the observations through the two spectral bands selected in the infrared window region. On this point, Maul and Sidran (1972) gave a comment that Anding and Kauth's (1970) result depends strongly on the atmospheric transmissivity model employed. However, the situation is different for the observations made from a low-flying aircraft, because the optical depth of this case is so thin that it is little affected by the transmissivity model. Accordingly, it seems that the application of the dual-channel method to the airborne infrared radiometer would be very hopeful unlike the satellite observations.

In this paper, the temperature calibration graph which was found by Anding and Kauth (1970) is derived analytically, and the accuracy of temperature measurements using the dual-channel airborne infrared radiometer is investigated under various atmospheric state.

2. The Principle of Compensation of Atmospheric Effect

The infrared radiation in the window region measured from the aircraft can be described by the radiative transfer equation

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$$N_W(\theta)=\exp(-t^*)\,[\varepsilon(\theta)B(T_b)+r(\theta)Ns(\theta)]+\int_0^{t^*}B(T_a)\exp(-t)\,dt \tag{1}$$

where

N_W is the detected radiance,

N_S is the downward sky radiance just above the sea surface,

B is the Planck function,

T_a is the air temperature,

T_b is the true sea surface temperature,

t is the optical path from the sensor in the direction of the objective,

t^* is the total optical path between the sensor and the objective,

θ is the inclination of the sensor,

ε is the emissivity of the sea surface,

r is the reflectivity of the sea surface.

The first term in the bracket on the right-hand side of this equation describes the contribution of non-black sea surface, the second term describes one of the reflections of sky radiation at the sea surface, and the last term describes the thermal radiation of the air column between the sensor and the objective.

Let us define the effective mean air temperature T_e by the equation

$$\int_0^{t^*}B(T_a)\exp(-t)\,dt\equiv B(T_e)\int_0^{t^*}\exp(-t)\,dt=B(T_e)(1-\exp(-t^*)) \tag{2}$$

Although T_e depends on wavelengths, the differences among them are so small as to be negligible, so far as we are concerned with thin atmosphere.

(1) can be also written,

$$N_W(\theta)=B(T_b)+r(\theta)(N_S(\theta)-B(T_b))+(1-\exp(-t^*))[(B(T_e)-B(T_b))\\ -r(\theta)(N_S(\theta)-B(T_b))] \tag{3}$$

with $\varepsilon(\theta)\approx 1-r(\theta)$.

In order to express (3) in terms of temperatures, we expand the radiance in Taylor's series of temperature, and obtain

$$T_W(\theta)-T_b=r(\theta)(T_S(\theta)-T_b+\delta T_{sb})+(1-\exp(-t^*))\\ [T_e-T_b+\delta T_{eb}-r(\theta)(T_s(\theta)-T_b+\delta T_{sb})] \tag{4}$$

where T_W and T_s stand for the brightness temperatures corresponding to N_W and N_s, respectively, which are called the detected temperature and the sky temperature in the following.

In the above expansion, as the differences (T_e-T_b) and (T_s-T_b) are not small in general, so we introduce the corrections δT_{eb}, and δT_{sb}, derived from the following equation, which mean the contribution from the higher terms of the Taylor expansion

$$B(T_{\substack{e\\s}})-B(T_b)=\frac{B(T_b)C_2\exp(C_2/T_b)}{T_b^2[\exp(C_2/T_b)-1]}(T_{\substack{e\\s}}-T_b+\delta T_{\substack{eb\\sb}}) \tag{5}$$

with $C_2=hc/\lambda k$

where h, c, λ and k stand for Planck's constant, the velocity of light, the wavelength and Boltzman's constant respectively. Table 1 shows how the corrections varies with $T_{\substack{e\\s}}$ and T_b between the wavelengths.

Rewriting (4), we get

$$T'_W(\theta) = T_b + (1-\exp(-t^*))[(T_e - T_b + \delta T_{eb}) - r(\theta)(T_s(\theta) - T_b + \delta T_{sb})] \quad (6)$$

Table 1 Corrections for expanding radiance as a linear function of temperature

$T-T_b$	$T_b=30°C$ T	$T_b=30°C$ $T-T_b+\delta T_b$ λ 8.7μ	$T_b=30°C$ $T-T_b+\delta T_b$ λ 11.0μ	$T_b=20°C$ T	$T_b=20°C$ $T-T_b+\delta T_b$ λ 8.7μ	$T_b=20°C$ $T-T_b+\delta T_b$ λ 11.0μ
+ 5°C	+ 35°C	+ 5.15°C	+ 5.10°C	+ 25°C	+ 5.16°C	+ 5.11°C
0	30	0	0	20	0	0
− 5	25	− 4.86	− 4.90	15	− 4.85	− 4.89
−10	20	− 9.42	− 9.60	10	− 9.38	− 9.56
−15	15	−13.72	−14.07	+ 5	−13.62	−14.01
−20	+ 10	−17.74	−18.39	0	−17.57	−18.25
−30	0	−24.99	−26.38	− 10	−24.60	−26.07
−40	− 10	−31.23	−33.57	− 20	−30.58	−33.03
−50	− 20	−36.53	−39.97	− 30	−35.58	−39.16
−60	− 30	−40.96	−45.61	− 40	−39.67	−44.49
−70	− 40	−44.59	−50.51	− 50	−42.96	−49.04
	−273	−55.28	−69.26	−273	−51.73	−64.88

$T-T_b$	$T_b=10°C$ T	$T_b=10°C$ $T-T_b+\delta T_b$ λ 8.7μ	$T_b=10°C$ $T-T_b+\delta T_b$ λ 11.0μ	$T_b=5°C$ T	$T_b=5°C$ $T-T_b+\delta T_b$ λ 8.7μ	$T_b=5°C$ $T-T_b+\delta T_b$ λ 11.0μ
+ 5°C	+ 15°C	+ 5.17°C	+ 5.12°C	+ 10°C	+ 5.19°C	+ 5.13°C
0	10	0	0	+ 5	0	0
− 5	+ 5	− 4.83	− 4.88	0	− 4.82	− 4.88
−10	0	− 9.33	− 9.53	− 5	− 9.30	− 9.50
−15	− 5	−13.50	−13.93	− 10	−13.43	−13.87
−20	− 10	−17.36	−18.09	− 15	−17.25	−18.01
−30	− 20	−24.18	−25.73	− 25	−23.94	−25.54
−40	− 30	−29.87	−32.45	− 35	−29.49	−32.13
−50	− 40	−34.54	−38.28	− 45	−33.99	−37.81
−60	− 50	−38.29	−43.27	− 55	−37.56	−42.62
−70	− 60	−41.23	−47.46	− 65	−40.33	−46.62
	−273	−48.29	−60.63	−273	−46.61	−58.56

where

$$T'_W(\theta) = T_W(\theta) - r(\theta)(T_s(\theta) - T_b + \delta T_{sb}) \quad (7)$$

The second term on the right-hand sides of (7) means the non-blackness correction termed by Saunders (1970). Using a PRT5 (manufactured by the Barnes Engineering Company), Saunders (1970) obtained the non-blackness correction values for various weather conditions as shown in Table 2. In this table, we can see that the non-blackness corrections are small. As already stated, we are concerned with the dual-channel method in this paper. In this case the non-blackness correction appears as a difference between those for two channels, so that this effect will be more smaller than the case for single channel. For example, even if the estimation error of the sky temperature is about 10°C, it will not affect the result more than by about 0.1°C. In practice, therefore, it will be sufficient to use the corrections determined empirically for typical weather conditions. Then in the following, we shall continue the discussion on the assumption that the non-blackness corrections are already known.

Table 2 Non-blackness Correction (1970, Saunders)

Cloud Type	Cloud Height, km	Range of Correction, °C
Clear	8	0.5 —0.7
Dense cirrostratus overcast	8	0.4 —0.55
Altocu or altostratus overcast	6	0.25—0.4
Stratus or stratocumulus overcast	3	0.2
Stratus or stratocumulus overcast	2	0.1
Stratus or stratocumulus overcast	1	0.1

As the transfer equation (6) holds for each spectral band of the dual-channel, we shall distinguish between them with subscripts 1 and 2 as follows:

$$T'_{W1}(\theta)=T_b+(1-\exp(-t^*))[(T_{e1}-T_b+\delta T_{e1b})-r_1(\theta)(T_{s1}(\theta)-T_b+\delta T_{s1b})] \quad (8)$$

$$T'_{W2}(\theta)=T_b+(1-\exp(-t^*))[(T_{e2}-T_b+\delta T_{e2b})-r_2(\theta)(T_{s2}(\theta)-T_b+\delta T_{s2b})] \quad (9)$$

The next step is to eliminate the terms of atmospheric effect from these formulae. Performing an operation $(8)-(9)\times(t_2^*/t_1^*)$, we obtain

$$T'_{W2}(\theta)-(t_2^*/t_1^*)T'_{W1}(\theta)=(1-t_2^*/t_1^*)T_b+\Delta, \quad (10)$$

where $\Delta\equiv(1-\exp(-t_2^*))[(T_{e2}-T_b+\delta T_{e2b})-r_2(T_{s2}-T_b-\delta T_{s2b})]$

$$-(t_2^*/t_1^*)(1-\exp(-t_1^*))[(T_{e1}-T_b+\delta T_{e1b})-r_1(T_{s1}-T_b+\delta T_{s1b})] \quad (11)$$

If Δ is negligible and t_2^*/t_1^* is constant, (10) shows that there is a linear relation between T'_{W1} and T'_{W2}. In other words, this means that when each pair of these temperatures is plotted as a function of atmospheric state, these points are distributed on a straight line which corresponds to each surface temperature T_b. Consequently, if once such linear relation can be established empirically or theoretically, we can easily find the true surface temperature from this relation independently to the atmospheric state. This also means that we can regard (10) as an analytical expression of the temperature calibration graph found by Anding and Kauth (1970, Fig. 6), and that Saunder's (1967) double angle measuring method corresponds to the case of $t_2^*/t_1^*=1/2$ in (10).

In the above discussion we have assumed that Δ is negligible and t_2^*/t_1^* is constant. In the following, we shall evaluate the effects of Δ and t_2^*/t_1^* on the result.

3. Discussion

As is evident from (11), Δ depends on the absorption coefficient and amount of absorbing gases, and the temperatures of sea surface, air and sky. Assuming various values for these parameters and calculating Δ from (11), we can estimate the surface temperature errors ΔT_b arising from neglecting Δ term in (10). Fig. 1 shows the behaviour of ΔT_b versues t_2^*/t_1^* with t_1^* as a parameter.

Let us denote the amount of water vapour between the sensor and the sea surface by u^* (pr. cm unit), where we assume that the contributions of other absorbing gases can be neglected in the relevant spectral regions. As extreme condition for the summer season in Japan, we assume $u^*=0.7$pr. cm at the altitude of about 300 metres. From this value, t_1^* can be calculated using Davis and Viezee's (1964) infrared transmissivity model, which was used by Maul and Sidran (1972) in their comment on the results of Anding and Kauth (1970). The value of t_1^* for the wavelength interval $8.3\sim9.1\mu$ becomes 0.1. In other seasons, it will become smaller in general. As is evident from Fig. 1, the curves $t_1^*<0.1$ are contained in the region $T_b<0.2°$C. As a result, we can conclude that so far as the measurements are not made in the extreme high humidity and from very high altitude, the neglect of Δ will not affect the result more than by 0.2°C.

Next we shall consider the constancy of t_2^*/t_1^*. The spectral region $8\sim13\mu$ is well known as the thermal infrared atmospheric window. However, this region contains many selective absorption lines of H_2O, CO_2 and O_3, so that band absorption at this region does not obey the Lambert law. Accordingly, even though the atmospheric composition is constant, it is feared that the constancy of t_2^*/t_1^* will not be held. In order to see this fact, we calculate $T'_{W1}-T_b$ and $T'_{W2}-T_b$ as a function of atmospheric state from (8) and (9). The results are shown in Fig. 2, where it will be noted that the ratio $(T'_{W2}-T_b)/(T'_{W1}-T_b)$ nearly equals to t_2^*/t_1^* from (10). In this calculation, the pair of spectral bands $8.3\sim9.1\mu$ and $10.5\sim11.4\mu$ is selected after Anding and Kauth (1970), although our bands are not exactly the same band widths as theirs, and we refer the reflectivity of the sea surface $r_1=0.02$, $r_2=0.01$ after Buettener and Kern (1965). For computing the infrared transmission we employ the model developed by Davis and Viezee (1964) as before. The other necessary parameters are shown in the upper left-hand corner of this figure.

As is clearly seen in Fig. 2, the plotted points $(T'_{W2}-T_b)/(T'_{W1}-T_b)$, i. e., t_2^*/t_1^* show a slightly curved line in accordance with the change of water vapour amount. However, their deviations from the straight line shown with $\leftarrow T_b$, which are chosen to minimize the rms orthogonal error, are very small. For reference, the straight lines corresponding to $T_b+0.2°$C and $T_b-0.2°$C are shown in the same figure. The fact that the plotted points all fall between these straight lines implies that t_2^*/t_1^* can be regarded as a constant to the extent of the aimed accuracy of 0.2°C. Here it may be noted that if $t_2^*/t_1^*\approx1$, all plotted points fall on the same straight line independent of surface temperature. In order to avoid this, therefore, we must choose such optimum spectral bands that the ratio of t_2^*/t_1^* is as small as possible.

Recently, Bignell (1970) suggested that the continuum absorptions of the window region would strongly depend on water vapour pressure, and their magnitudes are more than about three times as large as ones employed hitherto. However, his model is not employed in this paper, since his report deals with pure continuum absorptions apart from the selective absorption. However, it seems that even by Bignell's model the results would not be grossly different from the present ones, so far as we are concerned with a thin atmosphere.

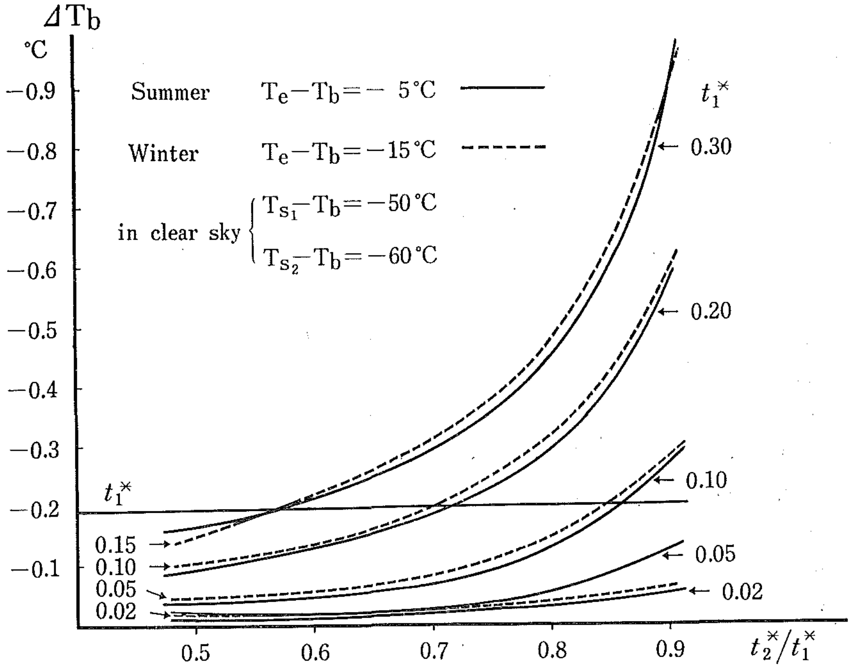

Figure 1 Errors arising from neglecting Δ term in the temperature calibration equation (10) as a function of the optical path ratio

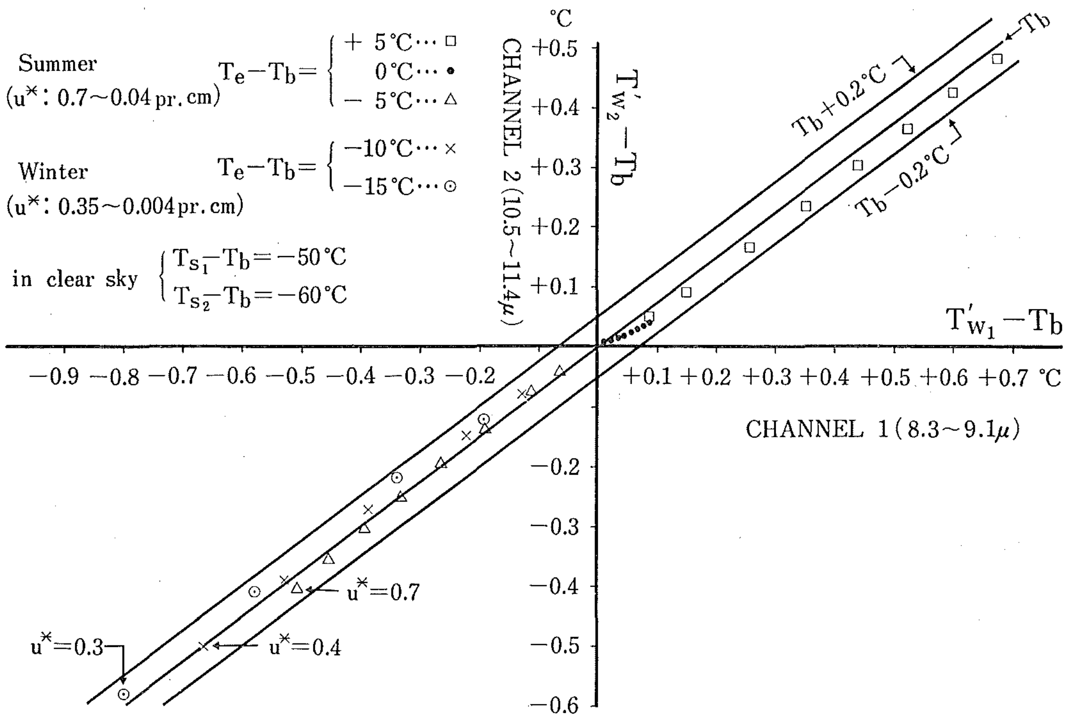

Figure 2 Detected temperature in channel 1 vs. that in channel 2 as a function of atmospheric state

4. Conclusions

As we have seen in the preceding section, it is expected that the dual-channel method is very useful for the determination of the true surface temperature using the airborne infrared radiometer. However, the atomospheric transmissivity model in the infrared window region has not been established yet. Consequently, it appears to be easier to determine t_2^*/t_1^* empirically from (8) in order to find the optimum pair of spectral bands. To do this, however, we must know in advance the values of T_b contrary to our purpose in this paper. Fortunately, the airborne radiometer observations make it possible to obtain data at various altitudes. From these data, the true surface temperatures are determined by the following procedures: 1) extrapolating to zero-altitude, and 2) applying the non-blackness correction mentioned in section 2. Once t_2^*/t_1^* is determined emprically, the true surface temperature can be simply obtained from the temperatures detected by the dual-channel infrared radiometer independent of the atmospheric state, the flight altitude and the inclination of the sensor.

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