Estimation of Sea Surface Temperatures From Two Infrared Window Measurements With Different Absorption

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Radiances measured at two different wavelengths or angles, with a resulting difference in absorption, can be used to determine the atmospheric attenuation of the surface radiance so that sea surface temperatures can be derived. Previous investigations used a correction equal to a constant times the difference in measured radiances. Some of these investigations were based on radiances calculated from models that underestimated absorption in moist atmospheres. When better transmittance models were used, the accuracy decreased. Radiances at 835 cm^{-1} are calculated for moist atmospheres at different zenith angles to test methods used to correct infrared measurements for atmospheric attenuation. Higher-order corrections are compared to first-order corrections and are shown to result in a significant increase in accuracy, reducing the rms error by one third, from 0.6 K to 0.4 K.

INTRODUCTION

Global sea surface temperatures are currently being derived from measurements obtained from the scanning radiometer (SR) on NOAA 2, which measures radiation in the 10- to 12-μm window [*Leese et al.*, 1971]. These measurements must be corrected for absorption by atmospheric water vapor. The present correction is obtained from atmospheric temperature and moisture profiles determined by the vertical temperature profile radiometer (VTPR) [*McMillin et al.*, 1973]. However, the scan size of the SR is much smaller than the scan size of the VTPR. In the tropics, where the correction is likely to be large, moisture variations can occur on a scale that is small in relation to the area represented by a single VTPR retrieval. There is also a question of stability when atmospheric corrections from the VTPR are used to obtain sea surface temperatures which are in turn used in the VTPR data processing.

A method of avoiding these problems by splitting the window channel has been proposed by *Anding and Kauth* [1970], *McMillin* [1971], and *Prabhakara et al.* [1972]. The essence of the method is that the radiance attenuation for atmospheric absorption is proportional to the radiance difference of simultaneous measurements at two different wavelengths, each subject to different amounts of atmospheric absorption. A difference in atmospheric absorption can also be obtained by measurements at the same wavelength but from different angles, as was demonstrated by *Saunders* [1967]. Although these authors used essentially the same method to correct for atmospheric attenuation, there are minor differences in the approaches used.

Saunders used aircraft measurements at zenith angles 0° and 55° (60° for warm humid atmospheres) to correct for sea surface temperatures. His corrections were smaller than those obtained from satellites because he was viewing through only the lower portion of the atmosphere. The correction was simply the difference between the two measurements. He claimed an accuracy of ±0.2 K or better.

Anding and Kauth [1970] used a regression program to determine relationships between measurements at two wavelengths and the sea surface temperature. They presented their results as lines of constant values of sea surface temperature on a plot of radiance at one wavelength versus radiance at the second wavelength. They claimed accuracies of ±0.2 K.

McMillin [1971] started with the radiative transfer equation and obtained an expression, which will be shown later, relating the surface radiance to measured radiances at two different wavelengths. This form demonstrated the physical reasons for the results obtained by *Anding and Kauth* [1970].

Prabhakara et al. [1972] used a different method of treating the dependence of the Planck function on wavelength. Since they used data from the Nimbus 4 infrared interferometer spectrometer (Iris) to obtain their measurements, their results are not dependent upon the use of a particular absorption model to simulate measurements. The danger of using simulated measurements even to select wavelengths with different total absorption is demonstrated by the results of *Anding and Kauth* [1970]. In their original paper they found that wavelengths of 10.96 μm and 9.19 μm gave the best results for the absorption model they used. *Maul and Sidran* [1972] repeated their calculations, using a different model and obtained wavelengths of 10.96 μm and 8.60 μm. *Anding and Kauth* [1972] used still a third model and obtained new wavelengths of 11.9 μm and 8.95 μm.

The techniques mentioned use a linear extrapolation of correction versus difference in radiance to determine the sea surface temperature. Furthermore, the results obtained by *Anding and Kauth* [1970] and *McMillin* [1971] were based on an absorption model which did not account for enough absorption in tropical atmospheres. To describe the absorption by water vapor in the window region, it is necessary to include a component proportional to the partial pressure of water vapor [*Bignell*, 1970; *Burch*, 1970]. *Anding and Kauth* [1972] used a revised absorption model that included this component to recalculate the results reported in 1970. The standard error in their estimate of sea surface temperature increased from 0.15 K to 1.59 K because of the increased absorption.

Absorption coefficients for water vapor, available for the SR channel and the VTPR 835-cm^{-1} channel, were used for the results reported here. Transmittances obtained with these coefficients are consistent with the results reported by *Bignell* [1970]. The atmospheric absorption in the window channels of these two instruments is almost the same, so that measurements at two different angles are used to obtain a difference in absorption. The ratio method described by *McMillin* [1971] is used to determine the error in the derived sea surface temperatures for a number of the 106 atmospheres contained in Appendix A of *Wark et al.* [1962]. Again the error increased because of the greater absorption in the new absorption model. Since errors with the accurate absorption models are beyond what is considered acceptable, it was decided to evaluate variations of the methods used to correct for atmospheric attenuation. A justification for the linear approach is given, and then several nonlinear approaches are compared. Modifications using nonlinear extrapolations reduce the error to the extent that errors of ±0.4 K are achieved.

DESCRIPTION OF THE METHOD

Surface temperatures can be obtained from two measurements in the window through a modification of the radiative transfer equation,

$$I(\nu) = B(\nu, T_s)\tau(\nu, p_0, \theta) + \int_{\tau(\nu, p_0, \theta)}^{1} B[\nu, T(p)]\, d\tau(\nu, p, \theta) \quad (1)$$

where I is the outgoing radiance, ν is the wave number, T is the atmospheric temperature at pressure p, T_s is the surface temperature, p_0 is the surface pressure, τ is the transmittance, θ is the zenith angle, and B is the Planck radiance. The mean value theorem can be used to simplify (1) to

$$I(\nu) = B(\nu, T_s)\tau(\nu, p_0, \theta) + \bar{B}_a(\nu)[1 - \tau(\nu, p_0, \theta)] \quad (2)$$

where $\bar{B}_a$ is the mean radiance of the atmosphere for the given τ and θ. If measurements at different wavelengths are used, the dependence of B and I on wavelength must be determined. For two wavelengths in the 10- to 13-μm window this can be accomplished by expanding the Planck function about ν to give

$$B(\nu_r, T) = B(\nu, T) + [\partial B(\nu, T)/\partial \nu][\nu_r - \nu] \quad (3)$$

and by expanding I in a similar manner to give

$$I(\nu_r) = I(\nu) + [\partial I(\nu, T)/\partial \nu][\nu_r - \nu] \quad (4)$$

where ν_r is a reference frequency and T is the temperature determined by the value of $B(\nu, T)$ which is equal to $I(\nu)$. For measurements in the atmospheric window region, values of T_s, the surface temperature, and $\bar{T}_a$, the temperature corresponding to $\bar{B}_a(\nu)$, are close to the value of T corresponding to $I(\nu)$. In addition, the dependence of $\partial B(\nu, T)/\partial \nu$ on the temperature is small in the 10- to 13-μm region. If values of ν and ν_r are sufficiently close, it is possible to neglect the dependence of $\partial B(\nu, T)/\partial \nu$ on temperature and to replace $\partial I(\nu, T)/\partial \nu$, $\partial B(\nu, T_s)/\partial \nu$, and $\partial \bar{B}_a(\nu, \bar{T}_a)/\partial \nu$ by $\partial B(\nu, T)/\partial \nu$ to give

$$I_i(\nu_r) = B(\nu_r, T_s)\tau(\nu_i, p_0, \theta) + \bar{B}_a(\nu_r)[1 - \tau(\nu_i, p_0, \theta)] \quad (5)$$

If values of $\bar{B}_a$ are nearly the same for two different values of $\tau(\nu_i, p_0, \theta)$, then differences in $I_i(\nu_r)$ can be related to differences in τ. For a typical atmosphere, *McMillin* [1971] found values of $\bar{B}_a(\nu_r)$ at 10.44 and 11.55 μm to be 275.2 and 275.1, respectively. If values of $\bar{B}_a(\nu_r)$ are assumed to be equal for two different wavelengths, (5) can be written for two values of ν and solved for B_s to give

$$B(\nu_r, T_s) = I_1(\nu_r) + [I_1(\nu_r) - I_2(\nu_r)] \cdot [1 - \tau(\nu_1, p_0, \theta)]/[\tau(\nu_1, p_0, \theta) - \tau(\nu_2, p_0, \theta)] \quad (6)$$

which can be written as

$$B(\nu_r, T_s) = I_1(\nu_r) + \gamma[I_1(\nu_r) - I_2(\nu_r)] \quad (7)$$

where γ is given by

$$\gamma = [1 - \tau(\nu_1, p_0, \theta)]/[\tau(\nu_1, p_0, \theta) - \tau(\nu_2, p_0, \theta)] \quad (8)$$

Solving (7) for $I_1(\nu_r)$ leads to the expression

$$I_1(\nu_r) = [B(\nu_r, T_s) + \gamma I_2(\nu_r)]/(1 + \gamma) \quad (9)$$

which describes a graph similar to the graph of the results shown by *Anding and Kauth* [1970].

For measurements at two angles rather than at two wavelengths the conversion to a common frequency is not necessary, and γ is given by

$$\gamma = [1 - \tau(\nu, p_0, \theta_1)]/[\tau(\nu, p_0, \theta_1) - \tau(\nu, p_0, \theta_2)] \quad (10)$$

Note that (8) and (10) differ only in that the parameter is allowed to change to obtain different values of τ.

For weak absorption, which occurs between the widely spaced lines in the window region, the transmittance can be approximated by

$$\tau(\nu) = \exp[-k(\nu)\mu] \approx 1 - k(\nu)\mu \quad (11)$$

where μ is the path length except in wet atmospheres. This gives γ a value of $k(\nu_1)/[k(\nu_2) - k(\nu_1)]$. Since values of $k(\nu)$ are only weakly dependent on atmospheric parameters, it is logical to try holding γ constant.

MODIFICATIONS

In preparation for the launch of NOAA 2 a program to calculate transmittances for the 835-cm^{-1} window channel was created [*McMillin et al.*, 1973]. This program used a model which had higher absorption for warm moist atmospheres than the model used by *McMillin* [1971]. Although most of the techniques used to correct for atmospheric attenuation are based on measurements at two different wavelengths, (8) and (10) demonstrate that there is no theoretical difference in the methods when measurements at two different angles are used instead. Since transmittances were available at a number of angles at one wavelength, transmittances at two angles (0° and 60°) were used to determine the accuracy of the method with the new transmittance model. However, the results apply to measurements at two different wavelengths as well.

A set of 32 atmospheres was selected from the set of 106 given by *Wark et al.* [1962] to evaluate the accuracy of derived sea surface temperatures. Since the necessary correction is greatest in a moist atmosphere, the more humid atmospheres were included in the sample. Values of the surface temperature, precipitable water, calculated radiances, and other parameters are given in Table 1. A subset consisting of every third atmosphere, starting with the first, was selected as a dependent data set. It became apparent that the assumptions involved in setting γ equal to a constant were violated. Values of γ were calculated by solving (7) for γ and were plotted (Figure 1). This plot suggests that γ should be a linear function of the difference $[I_1(\nu_r) - I_2(\nu_r)]$.

Table 2 gives the mean, rms, and standard errors of B (835 cm^{-1}, T_s), obtained by using three different definitions of γ: (1) the average value of γ, (2) the weighted average value of γ, where the weight is given by $[I_1(\nu_r) - I_2(\nu_r)]$, and (3) the value of γ given by a linear regression on $[I_1(\nu_r) - I_2(\nu_r)]$ resulting in

$$\gamma = \gamma_0 + \gamma_1[I_1(\nu_r) - I_2(\nu_r)] \quad (12)$$

The rms errors from the dependent sample are smaller than the rms errors from the independent sample, as is expected. For the independent sample, rms errors of 1.5216, 1.0017, and 0.6321 were obtained for B (835 cm^{-1}, T) for the three methods. These errors are equivalent to sea surface temperature errors of 0.84, 0.55, and 0.35 K at 300 K. Method 3 is an obvious improvement over methods 1 and 2, which use a linear extrapolation to correct for atmospheric attenuation.

In an operational satellite retrieval system, forecast atmospheric profiles are available. Since γ is a slowly varying

TABLE 1. Calculated Radiances and Other Parameters for 32 Atmospheres

Atmosphere	T_s, K	Precipitable Water, cm	sec θ	Other Parameters, $mW/(m^2\ sr\ cm^{-1})$			
				B_s	$\int_{\tau_s}^{1} B\,d\tau$	$B_s\tau_s$	Measured I
1	298.9808	4.231	1.0	126.9772	71.1973	46.6817	117.8790
			2.0		94.1510	18.5313	112.6823
2	293.0021	2.882	1.0	116.8137	36.3317	76.0310	112.3627
			2.0		56.8316	52.1533	108.9849
3	288.0000	2.500	1.0	108.6588	32.7620	77.0818	109.8438
			2.0		52.6205	57.6025	110.2230
4	283.1689	1.187	1.0	101.0862	12.8476	86.9234	99.7710
			2.0		22.5001	76.2259	98.7260
5	284.3912	1.275	1.0	102.9738	14.9809	86.4211	101.4020
			2.0		26.0435	74.1155	100.1590
6	277.8713	1.546	1.0	93.1267	14.7952	77.3108	92.1060
			2.0		25.5821	65.6678	91.2499
7	278.2230	0.646	1.0	93.6440	5.7550	87.3303	93.0853
			2.0		10.3851	82.2271	92.6122
8	262.0043	0.404	1.0	71.4541	2.0251	69.4257	71.4508
			2.0		3.7146	67.7270	71.4416
9	252.5352	0.253	1.0	60.0698	0.8116	59.2836	60.0952
			2.0		1.5163	58.5964	60.1127
10	297.9808	3.864	1.0	125.2458	60.9061	56.3640	117.2701
			2.0		85.3297	27.2126	112.5423
11	290.8649	1.745	1.0	113.2905	27.5080	84.0112	111.5192
			2.0		45.7195	64.4775	110.1970
12	286.5887	1.160	1.0	106.4157	11.7203	93.2124	104.9327
			2.0		20.4357	83.3235	103.7592
13	277.7775	0.956	1.0	92.9890	8.2590	83.8718	92.1308
			2.0		14.7048	76.7247	91.4295
14	282.0495	0.939	1.0	99.3741	10.2127	88.2719	98.4846
			2.0		18.0913	79.6733	97.7646
15	271.0000	0.687	1.0	83.3418	5.5626	77.7575	83.3201
			2.0		10.0181	73.2586	83.2767
16	270.7926	0.401	1.0	83.0559	2.6387	80.2031	82.8418
			2.0		4.8514	77.8017	82.6531
17	254.0000	0.258	1.0	61.7555	0.8156	60.9813	61.7969
			2.0		1.4964	60.3291	61.8255
18	242.0000	0.134	1.0	48.7546	0.2515	48.5210	48.7725
			2.0		0.4850	48.3029	48.7879
19	279.8262	1.083	1.0	96.0217	11.9945	83.0515	95.0460
			2.0		21.1568	73.0992	94.2560
20	273.9872	0.559	1.0	87.5207	3.1904	83.9160	87.1064
			2.0		5.7443	81.0079	86.7522
29	299.9830	5.038	1.0	128.7250	79.5439	37.3486	116.8925
			2.0		98.9709	11.8276	110.7985
30	298.0000	3.655	1.0	125.2790	61.8650	57.9331	119.7981
			2.0		87.3482	28.7765	116.1247
55	299.9786	5.486	1.0	128.7174	76.1791	37.1358	113.3149
			2.0		93.7573	11.6815	105.4388
56	299.9808	5.072	1.0	128.7212	78.9318	37.9013	116.8331
			2.0		98.4981	12.1703	110.6684
57	287.0000	3.244	1.0	107.0668	39.2396	62.7939	102.0335
			2.0		59.8250	38.6671	98.4921
58	300.9808	4.628	1.0	130.4777	72.0388	46.8684	118.9072
			2.0		94.1739	18.2842	112.4581
59	294.0000	4.312	1.0	118.4786	67.9994	42.2060	110.2054
			2.0		89.5501	16.1558	105.7059
60	291.7966	2.725	1.0	114.8193	44.2738	66.4180	110.6918
			2.0		67.4856	40.4105	107.8961
68	300.4311	4.224	1.0	129.5106	58.6143	61.1911	119.8054
			2.0		82.2740	31.1405	113.4145
69	299.4129	5.169	1.0	127.7293	81.2157	36.0214	117.2371
			2.0		99.9266	11.1045	111.0311
70	297.9829	5.012	1.0	125.2495	75.8664	37.9958	113.8622
			2.0		95.1083	12.5157	107.6240
71	291.3925	4.024	1.0	114.1548	59.0727	49.9664	109.0391
			2.0		82.2986	23.3814	105.6800

Atmospheres are from *Wark et al.* [1962].

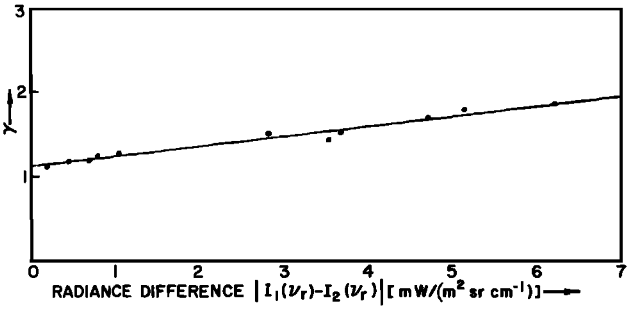

Fig. 1. γ as a function of differences in the radiance measured at two angles.

function of the atmosphere, a forecast might lead to a more accurate estimate of γ than is contained in (12), since given a forecast, it is possible to calculate γ from either (7) or (10). However, (10) is based on the assumption that values of $\bar{B}_a$ are equal. For atmosphere 60 (a wet atmosphere and therefore a severe test of the assumption), using (10) to calculate γ results in an error of 0.83 mW/(m^2 sr cm^{-1}) when the atmosphere is perfectly known. If an estimate of $B(\nu_r, T_s)$ as well as a forecast exists, then values of $I_1(\nu_r)$ and $I_2(\nu_r)$ can be calculated and used in (7) to solve for γ. This value of γ and measured values of $I_1(\nu_r)$ and $I_2(\nu_r)$ are used in (7) to solve for a new estimate of $B(\nu_r, T_s)$, which in turn leads to new calculated values of $I_1(\nu_r)$ and $I_2(\nu_r)$. This process is iterated until γ and $B(\nu_r, T_s)$ become constant. When the correct atmosphere is used, the solution converges to the correct value of $B(\nu_r, T_s)$, as is shown in Table 3, which contains values of γ and $B(\nu_r, T_s)$ for atmosphere 60. After four iterations, values of γ and $B(\nu_r, T_s)$ became constant with an error in the estimate of $B(\nu_r, T_s)$ of 0.0004 mW/(m^2 sr cm^{-1}). Several possibilities exist for an initial estimate of $B(\nu_r, T_s)$; the values shown in Table 3 were obtained by using the equivalent temperature of $I_1(\nu_r)$ as the starting values of T_s. A better initial value could be obtained by using (7) and (10) to get the first estimate of T_s.

In an operational system the true atmosphere would not be known. To evaluate the effect of imperfect knowledge of the atmosphere on the resulting solution, the method was used on every third atmosphere in Table 1, starting with the first. The next atmosphere in the table was used as a forecast for calculating $I(\nu)$. This was an extreme test because a forecast atmosphere would be expected to resemble the real atmosphere much more closely than the atmospheres used in this test do. Figure 2 shows the dependence of the absolute value of the resulting error on the absolute value of the difference in precipitable water between the real and forecast atmospheres. An error of 1 cm of precipitable water in the forecast produced an error of 0.6 mW/(m^2 sr cm^{-1}) in B (835 cm^{-1}, T_s). This error is small enough to be encouraging, but a problem was discovered when the calculations were performed for atmospheres 57 and 60. When the surface is cooler than the lower part of the atmosphere, it is possible for calculated values of $I_1(\nu_r)$ and $I_2(\nu_r)$ to be nearly equal, the result being that (7) does not give a good estimate of γ. In these cases a realistic value of γ from a regression could be used.

Because of the really poor first guess used in this test a comparison of a regression approach with (7) resulted in nine cases where the regression was better, two cases which did not converge, in that (7) gave a ridiculous value of γ, and two cases where the regression was worse. Since the accuracy of (7) depends on the quality of the forecast, a valid comparison would have to be made in an operational or nearly operational test.

TABLE 2. A Comparison of Errors of B (835 cm^{-1}, T_s) for Three Expressions of γ

Values of γ	rms	Average	σ
Dependent Sample Errors			
1.4272	1.0317	−0.4772	0.9148
1.6032	0.7318	−0.0712	0.7283
$1.1275 + 0.1124[I_1(\nu_r) - I_2(\nu_r)]$	0.3528	0.0364	0.3510
Independent Sample Errors			
1.4272	1.5216	−0.4682	1.4478
1.6032	1.0017	−0.1835	0.9847
$1.1275 + 0.1124[I_1(\nu_r) - I_2(\nu_r)]$	0.6321	0.0125	0.6320

ν_r is equal to 835 cm^{-1}.

TABLE 3. Test of Iteration Solution for Atmosphere 60

Iteration	γ	$B_s[\nu_r, T(p_0)]$,* mW/(m^2 sr cm^{-1})
0	0	110.6918
1	1.2831	114.2790
2	1.4588	114.7700
3	1.4748	114.8150
4	1.4762	114.8189

* The actual value of $B_s[\nu_r, T(p_0)]$ is 114.8193 mW/(m^2 sr cm^{-1}).

CONCLUSIONS

Radiances at two different wavelengths or angles can be used to obtain an estimate of the correction required for measurement of sea surface temperatures from satellites. Methods described in previous papers are equivalent to making corrections that are proportional to the difference in the two measurements. At least two alternatives exist: one based on regression and one based on forecast atmosphere. The accuracy of the second method can be evaluated only if the quality of the forecast is known. However, it is unlikely that the forecast approach would result in a significant increase in accuracy over the regression approach except in very moist atmospheres. Even in these cases the forecast water vapor profile would have to be accurate before any improvement would result. The nonlinear regression solution is a significant improvement over linear methods previously reported.

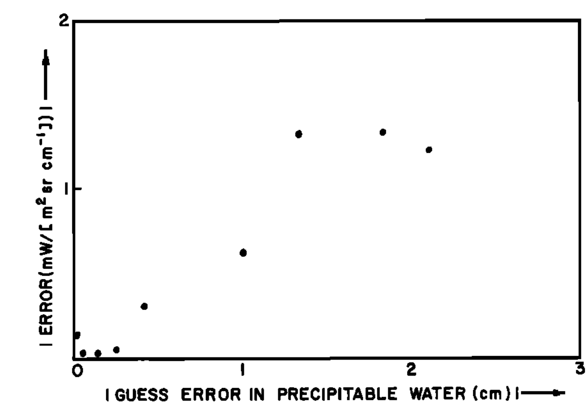

Fig. 2. Dependence of solution error as a function of the error in forecast water vapor amount.

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