

Review article

Progress in the remote sensing of land surface temperature and ground emissivity using NOAA–AVHRR data

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Abstract. The extensive requirement of land surface temperature (LST) for environmental studies and management activities of the Earth's resources has made the remote sensing of LST an important academic topic during the last two decades. Many studies have been devoted to establishing the methodology for the retrieval of LST from channels 4 and 5 of Advanced Very High Resolution Radiometer (AVHRR) data. Various split-window algorithms have been reviewed and compared in the literature to understand their differences. Different algorithms differ in both their forms and the calculation of their coefficients. The most popular form of split-window algorithm is $T_s = T_4 + A(T_4 - T_5) + B$, where T_s is land surface temperature, T_4 and T_5 are brightness temperatures of AVHRR channels 4 and 5, A and B are coefficients in relation to atmospheric effects, viewing angle and ground emissivity. For the actual determination of the coefficients, no matter the complexity of their calculation formulae in various algorithms, only two ways are practically applicable, due to the unavailability of many required data on atmospheric conditions and ground emissivities *in situ* satellite pass. Ground data measurements can be used to calibrate the brightness temperature obtained by remote sensing into the actual LST through regression analysis on a sample representing the studied region. The other way is standard atmospheric profile simulation using computer software such as LOWTRAN 7. Ground emissivity has a considerable effect on the accuracy of retrieving LST from remote sensing data. Generally, it is rational to assume an emissivity of 0.96 for most ground surfaces. However, the difference of ground emissivity between channels 4 and 5 also has a significant impact on the accuracy of LST retrieval. By combining the data of AVHRR channels 3, 4 and 5, the difference can be directly calculated from remote sensing data. Therefore, much more study is required on how to accurately determine the coefficients of split-window algorithms in the application of remote sensing to examine LST change and distribution in the real world.

1. Introduction

Land surface temperature (LST) is an important factor controlling most physical, chemical and biological processes of the Earth. Knowledge of LST is necessary for

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many environmental studies and management activities of the Earth's resources (Li and Becker 1993). In order to monitor macro-scale spatial changes of surface temperature, scanners designed for sensing in the thermal bands are placed onboard platforms for remote sensing of the Earth's resources from space (Sabins 1986).

The extensive application and significant importance of temperature in environmental studies and management is the main force driving the study of LST in remote sensing. Under the availability of thermal sensing data such as channels 4 and 5 of Advanced Very High Resolution Radiometer (AVHRR) data as well as Landsat Thematic Mapper 6 (TM6), the study of LST has become one of the hottest topics in remote sensing during the last two decades (Vogt 1996). Many studies have been carried out on LST and the related ground emissivity from both technological aspects and application to specific areas (Becker 1987, Holbo and Luvall 1989, Cooper and Asrar 1989, Vidal 1991, Seguin *et al.* 1994, Choudhury *et al.* 1995, Schultz and Halpert 1995, Cracknell and Xue 1996, Caselles *et al.* 1997). The achievements are numerous. There have been quite a large number of publications on land surface temperature regimes.

With the development of remote sensing science, various algorithms have been proposed for the remote sensing of LST. Different algorithms and methods are based on different considerations and are suitable for different conditions. From the studies published by various scientists all over the world, one can trace the progress made in the remote sensing of surface temperature both in terms of theoretical algorithm and application. However, the reported achievements in this important academic area are scattered among the mass of individual publications, especially in papers published in different remote sensing journals. Although a few review papers on surface temperature studies have been published (Prata and Platt 1991, Prata *et al.* 1995, Vogt 1996), they are with different focus and for different purposes. Up till now there has been a lack of synthetic retrospection on the most recent progress in the remote sensing of LST as a whole which would enable us to look towards the important areas of the academic realm for further study with various purposes. It is necessary to compare the published studies for a comprehensive review of the progress in the academic area.

In this paper, the objective is to review the progress in research on the remote sensing of LST during the last two decades. We will begin by examining the theoretical aspects of the relationship between temperature and radiance transfer principles. Then we will look at the various algorithms proposed for calculating LST from remote sensing data and the calibration of the calculation with ground emissivity. Finally, a conclusion will be made as to the progress of LST studies in remote sensing in order to reveal the important academic issues.

2. Theoretical basis for the remote sensing of LST

LST is generally defined as the skin temperature of the ground. For the bare soil surface, LST is the soil surface temperature. However, the ground of the earth is far from a skin or homogeneous surface with two dimensions (Vogt 1996). Usually, it is composed of various objects on the surface and some of them such as vegetation may be best described in three dimensions. This situation makes the understanding of LST obscure, such as the case of vegetated ground. The remote sensing of LST is based on the thermal spectral (long wave) radiation from the ground. Thus, LST of dense vegetated ground can be viewed as the canopy surface temperature of the vegetation, and in sparse vegetated ground, it is the average temperature of

the vegetation canopy, vegetation body and the soil surface under the vegetation. Another factor leading to the difficult understanding of LST is that the surface is not homogeneous at the spatial resolution (pixel scale) of remote sensing data. Usually, LST changes obviously in a small distance such as 1 m (Ottlé and Vidal-Madjar 1992). However, the spatial resolution of most remote sensing data for LST is low compared with the difference of LST on the ground. For example, the pixel size for NOAA-AVHRR is 1.1 km, and for Landsat TM channel 6 it is 120 m. Thus, LST in remote sensing means the average surface temperature of the ground under the pixel scale mixed with different fractions of surface types (Kerr *et al.* 1992).

The theoretical basis for the remote sensing of LST is that total radiative energy emitted by ground surface increases rapidly with increase in temperature. The spectral distribution of the energy emitted by a ground object also varies with temperature. According to Wien's Displacement Law on the relationship between spectral radiance and wavelength, for the Earth with an ambient temperature of 300 K, the peak of its spectral radiance occurs at about $9.6 \mu\text{m}$ (Lillesand and Kiefer 1987). Therefore, theoretically, the thermal energy in relation to the physical temperature of the ground surface can be remotely observed by using sensors operating at wavelength around $10 \mu\text{m}$, which have been defined as thermal channels in remote sensing systems. The obtained temperature of the ground surface on the satellite level is called the brightness temperature (Reutter *et al.* 1994).

On the other hand, the spectral characteristics of the atmosphere indicates that there is an atmospheric window in the spectral region 8–14 μm , where atmospheric absorption is minimum and through which the energy source of ground surface can transmit without great losses. Thus, ground surface temperature can be remotely sensed using the channels within the atmospheric window at the thermal spectral wavelength. Data from NOAA-AVHRR channels 4 and 5 operating respectively at 10.5–11.3 μm and 11.5–12.5 μm as well as Landsat TM channel 6 operating at 10.4–12.5 μm can be used to estimate surface temperature.

2.1. Planck's radiation equation and brightness temperature

In accordance with the black body radiation principle, the spectral radiance emitted from ground surface as a black body can be described by Planck's radiation spectral equation (Humes *et al.* 1994):

$$B_{\lambda}(T) = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)} \quad (1)$$

where $B_{\lambda}(T)$ is the spectral radiance of the ground surface, generally measured in $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$, λ is wavelength in m, h is Planck's constant ($h = 6.626076 \times 10^{-34} \text{ J s}$), k is Boltzmann's constant ($k = 1.380658 \times 10^{-23} \text{ J K}^{-1}$), T is temperature in K, and c is the speed of light ($c = 2.99792458 \times 10^8 \text{ m s}^{-1}$).

However, the black body is a theoretical concept and most objects on the Earth's surface do not behave as black bodies. The ratio between the radiation emitted by an object and that by a black body at the same temperature is defined as the object's emissivity ε_{λ} , which must be considered in Planck's equation (Saraf *et al.* 1995)

$$B_{\lambda}(T) = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)} \varepsilon_{\lambda} \quad (2)$$

Spectral emissivity is measured to be in the range $0 \leq \varepsilon \leq 1$ and is dimensionless. For most natural materials of the ground surface, the emissivity usually ranges between

0.91 and 0.98 in the thermal wave region 8–14 μm (Lillesand and Kiefer 1987, Humes *et al.* 1994, Vogt 1996).

If there is no attenuation in the process of transferring the emitted spectral radiance from the surface through the atmosphere to the remote sensor, the temperature of the ground object can be theoretically determined, if the emitted spectral radiance $B_{\lambda}(T)$ is measured, by inverting Planck's radiation equation as follows:

$$T = \frac{c_2}{\lambda \ln([\varepsilon_{\lambda} c_1 / \lambda^5 B_{\lambda}(T)] + 1)} \quad (3)$$

where c_1 and c_2 are the constants with $c_1 = 2\pi^5 hc^2 = 3.741771995 \times 10^{-16} \text{ W m}^2$ and $c_2 = hc/k = 1.43876869 \times 10^{-2} \text{ m K}$.

However, the spectral radiance of the ground surface is usually measured by a sensor installed in an airplane or satellite which is far from the ground. Therefore, the transmission of the emitted spectral radiance through the atmosphere to the sensor is affected by a number of factors, which make the retrieval of ground surface temperature from the remote sensing data more complicated. In the thermal wavelength, usually the atmosphere has three very important effects on the spectral radiation transmission: absorption, upward atmospheric radiance and bi-directional reflection of the downward atmospheric radiance (França and Cracknell 1994). Therefore, the spectral radiance reaching the sensors is not only that emitted by ground objects and attenuated by atmospheric absorption, but also includes the radiance emitted by the atmosphere and the reflected component of the downward atmospheric radiance. At the same time, different viewing angles of the sensor and the characteristics of the ground objects also have significant effects on the observed radiance from space (Ignatov and Dergileva 1995, Wan and Dozier 1996).

2.2. The satellite-observed radiation

The remote sensing of LST is based on the observed radiation, which mainly depends on the radiance emitted by ground surface, though the atmosphere also has many effects. Split-window algorithms for retrieval of LST are derived from the radiance transfer equation of thermal wavebands. Usually, the formation of the equation is based on the following assumptions: (1) the Earth's surface is a Lambertian body; (2) a cloud-free atmospheric condition exists; and (3) local atmospheric thermodynamic equilibrium conditions prevail. Therefore, the remotely sensed radiance $I_i(T_i)$ for a given brightness temperature (T_i) in channel i is viewed at zenith angle θ and has undergone attenuation by atmospheric absorption, emission and scattering on its path from the surface of the Earth to the altitude of the satellite sensor which usually is in space at several hundred kilometres from the ground (França and Cracknell 1994).

The absorption process within the atmospheric window of the thermal waveband is due to water vapour, carbon dioxide, nitrogen oxide, ozone oxide, methane and carbon monoxide in the order of decreasing importance. Comparing the magnitude of their effects, water vapour is the most important factor influencing the radiance transfer in the thermal spectral range. It is also highly variable in concentration and distribution, which makes any modelling difficult. The influence of other gases is much smaller compared to that of water vapour because they are relatively stable and uniform in concentration and distribution. So, their effects are, for simplicity, usually disregarded in the derivation of models for LST correction.

Different considerations to the radiation equation and different simplification to

the atmospheric effects have resulted in different algorithms for the retrieval of LST. According to Price (1984), the satellite-observed radiation $I_\lambda(T_\lambda)$ at the top of the atmosphere can be expressed as

$$I_\lambda(T_\lambda) = B_\lambda(T_s) - \int_0^{\tau_\lambda} d\tau'_\lambda \exp(-\tau'_\lambda) [B_\lambda(T_s) - B_\lambda(T_a(\tau_\lambda - \tau'_\lambda))] \quad (4)$$

where $B_\lambda(T_s)$ is the ground surface radiation as a black body at temperature T_s and wavelength λ , $B_\lambda(T_s(\tau_\lambda - \tau'_\lambda))$ is the atmospheric radiation at the atmospheric temperature $T_a(\tau_\lambda - \tau'_\lambda)$ at optical thickness $(\tau_\lambda - \tau'_\lambda)$, in which τ_λ and τ'_λ are the optical thickness from the ground level and the atmospheric height, respectively, to the sensor altitude in wavelength λ . Therefore, the second term of equation (4) represents the total atmospheric effects. Obviously, this equation treats the total atmospheric effects (absorption, upward and downward emitted radiance) as a negative term attenuating the original emitted radiance $B_\lambda(T_s)$ of the ground surface.

This equation can not be directly solved because it contains many unknowns. Thus, it is necessary to consider its simplification. For simplification, Price (1984) neglected aerosol scattering in the 10–13 μm waveband and assumed the ground surface to be a black body. Thus, he only emphasized on the absorption and re-emission of radiation by water vapour, which has the most important impact in the atmosphere on the spectral transmission of thermal energy through the lower atmosphere. After applying Taylor's expansion to Planck's equation and keeping only its first-order terms, Price (1984) got:

$$T_\lambda = T_s(1 - \tau_\lambda) + \int_0^{\tau_\lambda} d\tau'_\lambda T(\tau_\lambda - \tau'_\lambda) \quad (5)$$

Let $d\tau'_\lambda = k_\lambda dU$ and $f(U) = \tau_\lambda - \tau'_\lambda$, where U represents the atmospheric absorber and k_λ represents the absorption coefficient of the absorber at wavelength λ , equation (5) can be written as

$$T_\lambda = T_s(1 - \tau_\lambda) + \int_0^{\tau_\lambda} k_\lambda T(U) dU \quad (6)$$

Defining the total effect of atmospheric conditions as $A_\lambda U_t = \int k_\lambda T(U) dU$ and assuming the optical thickness $\tau_\lambda \ll 1$ at the thermal band, equation (6) changes into

$$T_\lambda = T_s + A_\lambda U_t \quad (7)$$

A split-window algorithm for LST can be solved after applying equation (7) to the thermal channels 4 and 5 of AVHRR data for eliminating the atmospheric determinant U_t .

In order to formulate a split-window algorithm for LST, Coll *et al.* (1994a) expressed the thermal radiance $I_i(T_i)$ obtained by the satellite scanner in channel i as follows:

$$I_i(T_i) = \varepsilon_i \tau_i(\theta) B_i(T_s) + L_i^\uparrow(\theta) + (1 - \varepsilon_i) \tau_i(\theta) \gamma_i L_i^\downarrow(\theta = 0) \quad (8)$$

where T_s and T_i are, respectively, the LST and channel i brightness temperatures; $\tau_i(\theta)$ is total atmospheric transmittance in channel i at viewing angle θ ; $L_i^\uparrow(\theta)$ is the upward radiance emitted by the atmosphere, $L_i^\downarrow(\theta = 0)$ is the downward radiance emitted by the atmosphere in nadir direction, and γ_i is a parameter that depends on the channel and the type of atmosphere.

For derivation, several assumptions have to be made. A black body surface is generally assumed. Thus, only the atmospheric emission and absorption are accounted for. Besides, it is necessary to define a mean radiation temperature T_{ai} of the atmosphere to which the radiance emitted by the atmosphere, $L_i^{\uparrow}(\theta)$, can be referred. Finally, Planck's function can be simplified by linearization in terms of temperature. By using Taylor's expansion to the Planck function and only taking the first order of the expansion, equation (8) can be written with a good approximation as

$$T_s - T_i = [(1 - \tau_i(\theta))/\tau_i(\theta)](T_i - T_{ai}) \quad (9)$$

Actually, the assumption of a black body surface is not strictly true. Thus, the effect of ground emissivity has to be considered in the derivation. Adding emissivity correction complementary, equation (9) becomes

$$T_s - T_i = [(1 - \tau_i(\theta))/\tau_i(\theta)](T_i - T_{ai}) + b_i(1 - \varepsilon_i)/\varepsilon_i \quad (10)$$

where b_i has dimensions of temperature and can be approximated as follows:

$$b_i = \frac{T_i}{n_i} + \gamma_i \left(\frac{n_i - 1}{n_i} T_i - T_{ai} \right) [1 - \tau_i(0)] \quad (11)$$

in which $\tau_i(0)$ is the atmospheric transmittance for nadir viewing and n_i is a radiometric parameter which depends on the channel and temperature interval considered and can be approximated as follows:

$$B_i(T) \cong c_i T^{n_i} \quad (12)$$

in which c_i and n_i are constants for channel i . Given a temperature range of 280–320 K, n_i is equal to 4.58972 for Planck's function in the spectral range 8–14 μm (França and Cracknell 1994) and $c_i = 1$ in the range of 10–12 μm for channels 4 and 5 of AVHRR (Price 1983). Specifically, Schmutge *et al.* (1991) gave the value of n_i for channel 4 and 5 as $n_4 = 4.822$ and $n_5 = 4.472$ while the constant is given as $n_4 = 4.51921$ and $n_5 = 4.12636$ by França and Cracknell (1994). Applying equation (11) to the thermal channels 4 and 5 of AVHRR data for eliminating the term T_{ai} , a split-window algorithm can be derived.

Two atmospheric correction models have been developed by França and Cracknell (1994) for the retrieval of LST from remote sensing data in the thermal wavebands: an airborne model for data obtained from low-flying platforms and a split-window algorithm for AVHRR data. For the later, the following radiance transfer equation has been used for the derivation on the basis of the assumption that spectral emissivity and transmittance are nearly independent of temperature (França and Cracknell 1994):

$$I_i(T_i) = \varepsilon_i \tau_i(\theta, 0, Z) B_i(T_s) + \int_0^Z B_i(T_{az}) \frac{\partial \tau_i(\theta, z, Z)}{\partial z} dz + 2\tau_i(1 - \varepsilon_i) \int_0^{\pi/2} \int_{-\infty}^0 B_i(T_{az}) \frac{\partial \tau_i(\theta', z, 0)}{\partial z} \cos \theta' \sin \theta' dz d\theta' \quad (13)$$

where $I_i(T_i)$ represents the spectral radiance recorded by a given channel i ($i=4$ or 5 for AVHRR), ε_i is the ground emissivity in channel i , Z is the altitude of the sensor and z is the average atmospheric altitude between the ground and the sensor altitude Z , $\tau_i(\theta, 0, Z)$ is the spectral transmittance of the atmosphere between the ground and

the sensor altitude Z at channel i with viewing angle θ , and θ' is the zenith angle of the downward atmospheric radiance.

The meaning of each term at the right-hand side of equation (13) is almost the same as that in equation (8), although their expression of details and accuracy are quite different. The first term of the right-hand side in equation (13) represents the radiance of the land surface at temperature T_s with emissivity ε_i and atmospheric transmittance τ_i for channel i . The second term represents the radiance emitted by the atmosphere and received directly by the sensor. And the third term represents the downward atmospheric radiance that is reflected by the surface and then attenuated in its upward path to the sensor. Therefore, $B_i(T_{az})$ means the atmospheric radiance in channel i for atmospheric temperature T_{az} at altitude z . And $\tau_i(\theta, z, Z)$ is the atmospheric effect on the atmospheric radiance $B_i(T_{az})$ between altitudes z and Z , and $\tau_i'(\theta', z, 0)$ is the atmospheric effect on the $B_i(T_{az})$ on the way of downward radiance.

After some rational assumptions for the whole atmosphere have been made for simplification and Taylor's expansion have been applied to Planck's function, the above radiance transfer equation becomes

$$T_s - T_i = \frac{1 - \varepsilon_i}{\varepsilon_i} L_i + \frac{T_i - T_a}{\varepsilon_i \tau_i(\theta) \cos(\theta)} W_i - 2 \frac{1 - \varepsilon_i}{\varepsilon_i} (T_a - T_i + L_i) W_i \quad (14)$$

where $W_i = a_{1i}(\theta)w + a_{2i}(\theta)w^2$, in which w is the water vapour in the atmosphere and a_{1i} and a_{2i} are the parameters of the atmospheric state in channel i , T_a represents average atmospheric temperature and L_i is given by $L_i = T_i/n_i$, in which n_i is a constant for channel i defined in equation (12). Generally, the parameters of the atmospheric state, a_{1i} and a_{2i} , are calculated from simulation data by running the LOWTRAN 7 program, which is used to provide the standard atmospheric conditions. A split-window algorithm can be derived after equation (14) is applied to channels 4 and 5 of AVHRR data for eliminating the terms T_a .

2.3. A simple method to compute brightness temperature

The retrieval of LST from AVHRR data needs the brightness temperature for channels 4 and 5 to be given at first. However, the calculation of a black body's temperature by Planck's equation is complex numerically because it needs to consider the spectral response functions of the temperature to the radiance in different wavelengths. Usually, it is done by a look-up table, which is calculated by central wavelength techniques for different temperature ranges (Wooster *et al.* 1995). A simple method to compute brightness temperature from the observed radiance is provided by Sullivan (1995). The relationship of the radiance versus temperature is a simple monotonic function, which can be fitted accurately into a quadratic equation (Sullivan 1995):

$$I_i(T_i) = I_0 + a(T_i - T_0)^2 \quad (15)$$

where $I_i(T_i)$ is the observed radiance at brightness temperature T_i in channel i . By inverting the equation, we can get the brightness temperature from the observed radiance:

$$T_i = T_0 + [(I_i(T_i) - I_0)/a]^{1/2} \quad (16)$$

in which I_0 , a and T_0 are the parameters given in table 1, from which we can see that the values of the three parameters vary only slightly among the AVHRRs, which

Table 1. Values of I_0 , a and T_0 for four AVHRRs (after Sullivan 1995).

	Channel 4			Channel 5		
	T_0	I_0	a	T_0	I_0	a
NOAA-12	173.55	8.00	0.00661	161.70	7.86	0.00630
NOAA-11	174.39	8.00	0.00662	162.41	7.91	0.00632
NOAA-09	174.65	8.00	0.00663	162.90	7.92	0.00634
NOAA-07	174.32	8.00	0.00662	162.27	7.90	0.00632

were built to meet the same specifications. The difference between the estimation by this simple method and the value found from the look-up table calculated from Planck's radiance equation is generally about 0.3 K. If the correction curve between radiance and temperature is added, the method can give a very accurate brightness temperature estimation (Sullivan 1995).

Therefore, by using either Planck's radiance equation or the simple method provided by Sullivan (1995), we can achieve the brightness temperature retrieval of LST from remote sensing data. In order to estimate LST, the brightness temperature must be calibrated by considering various effects between the original emitted radiance and the measured radiance (Sugita and Brutsaert 1993). As we will see in the next sections, many algorithms and models have been developed by scientists for this purpose.

3. Split-window algorithm for land surface temperature

Because of its easy accessibility, National Oceanic and Atmospheric Administration (NOAA) AVHRR data have been extensively applied to the examination of LST for different purposes. A number of split-window algorithms for retrieval of LST from channels 4 and 5 of AVHRR data have been proposed in the last few decades. Though these algorithms differ greatly in calculation, two categories can be identified according to the form of their expression. We attempt here to compare some split-window methods so that the full understanding of their differences can be acquired.

3.1. General form of split-window algorithm

If T_4 and T_5 are respectively the brightness temperatures in channels 4 and 5 of AVHRR data, the general form of the split-window equation can be written as

$$T_s = T_4 + A(T_4 - T_5) + B \quad (17)$$

where T_s represents the land surface temperature, A and B are the coefficients determined by the impact of atmospheric conditions and other related factors on the thermal spectral radiance and its transmission in channels 4 and 5.

The split-window algorithm developed by Price (1984) for NOAA-7 has been extensively quoted for LST study. After making several simplifications to the atmospheric effects on the radiation transmission from the ground to the sensor, Price (1984) obtained his split-window algorithm, having the general form of

equation (17). Coefficient B in the algorithm of Price (1984) is given as $B=0$ and coefficient A is as

$$A = \frac{1}{A_r - 1} \quad (18)$$

where $A_r = A_5/A_4$ is the function of atmospheric conditions, especially the contributions of atmospheric radiation emission and absorption in the thermal region. The successful use of the split-window algorithm relies on the accuracy of determination of the ratio A_r as a result of atmospheric effects. However, due to lack of detailed data on the atmospheric profile *in situ* satellite pass, it is difficult to directly compute the ratio.

It is assumed that surface temperature is uniform in a small area with uniform surface features. Thus, the observed variation of brightness temperature is due to the atmospheric nonuniformity. Based on this assumption, Price (1984) estimated A_r as the ratio of the observed variation of brightness temperature of a small area on the studied image with relatively uniform surface features under the pixel scale. Considering the possible impacts of instrument noise of the sensor and the nonuniformity of surface brightness temperature of the small area, it is preferable to computer the ratio A_r from averaged quantities. Thus, $A_r = \Delta T_5/\Delta T_4$, in which ΔT_4 and ΔT_5 are the average variation of brightness temperature of the small area in channels 4 and 5, respectively. Price (1984) found that the ratio value of $A_r = 1.30$ can be rational for most ground surfaces. Thus, equation (18) becomes

$$T_s = T_4 + 3.33(T_4 - T_5) \quad (19)$$

Obviously, this formula, if applying to other regions, may subject to possible errors due to the difference from the small area used to compute A_r and many unknown atmospheric effects.

In order to improve the accuracy of the split-window algorithm, several modifications to the method of Price (1984) have been published since the mid-1980s. Based on their radiance transfer equation (8), which considers the satellite zenith observation θ and surface emissivity ε_i of channel i , Coll *et al.* (1994a) developed a new split-window algorithm for LST estimation. Though the algorithm keeps the general form of equation (17), its coefficients are given quite differently due to different considerations to the atmospheric effects and the ground emissivity. The two coefficients are given by Coll *et al.* (1994a) as follows:

$$A = [1 - \tau_4(\theta)] / [\tau_4(\theta) - \tau_5(\theta)] \quad (20)$$

$$B = \frac{1 - \varepsilon_4}{\varepsilon_4} b_4 + A \tau_5(\theta) \left[\frac{1 - \varepsilon_4}{\varepsilon_4} b_4 - \frac{1 - \varepsilon_5}{\varepsilon_5} b_5 \right] \quad (21)$$

in which b_4 and b_5 can be given by equation (11) or approximated by equation (50) for channels 4 and 5. In order to approximate b_4 and b_5 by equation (50), a sample representing the studied region needs to be taken from the AVHRR image. Obviously, the coefficient A is only the function of atmospheric conditions. This is the same as that in Price (1984). However, the coefficient B given by Coll *et al.* (1994a) is related to both atmospheric effects and ground emissivity, while it is equal to 0 in Price (1984).

Coll *et al.* (1994a) calculated the two coefficients A and B for a set of atmospheric profiles in their study. They found that water content in the atmosphere, when it is

above 1 g/cm^2 , plays the most important effect in determining A , which is estimated to be 2.5–2.8 for the water content ranging from 1 to 3.5 g cm^{-2} . After analysing the impact of atmospheric transmittance on A , Coll *et al.* (1994a) proposed a modified split window equation to their algorithm. The modified equation still has the general form of equation (17), but coefficient A is determined as follows:

$$A = d_0 + d_1(T_4 - T_5) \quad (22)$$

where d_0 and d_1 are constants with $d_0 = 1.29$ and $d_1 = 0.28$. Coefficient B is given as the same in equation (21). This modified equation can give an error of 0.33 K in estimation of T_s . Obviously, coefficient A in the modified equation is not a constant but depends linearly on the brightness temperature difference between channels 4 and 5 of AVHRR data. This is quite difference from equations (18) and (20).

Based on the structural components of ground surfaces, a methodology has been developed by Sobrino *et al.* (1991) for the atmospheric and emissivity corrections to the brightness temperature of AVHRR data. Though the algorithm proposed by Sobrino *et al.* (1991) also has the general form as equation (17), its two coefficients A and B are given in a much more complicated form than the algorithms of Price (1984) and Coll *et al.* (1994a). The effects of surface emissivities, atmospheric absorption coefficients and total water vapour amount in channels 4 and 5 are directly expressed in the determination of the coefficients A and B by Sobrino *et al.* (1991) as follows:

$$A = \frac{\alpha_5 \beta_4 + \alpha_4 \beta_5 w}{\alpha_4 \beta_5 - \alpha_5 \beta_4} \quad (23)$$

$$B = \frac{(1 - \varepsilon_4) \alpha_4 \beta_5}{\varepsilon_4 \alpha_4 \beta_5 - \alpha_5 \beta_4} (1 - 2k_{4w}) L_4 - \frac{(1 - \varepsilon_5) \alpha_5 \beta_4}{\varepsilon_5 \alpha_4 \beta_5 - \alpha_5 \beta_4} (1 - 2k_{5w}) L_5 \quad (24)$$

Here w donates the amount of water vapour in the atmosphere (g cm^{-2}), k_i is the absorption coefficient of the whole atmosphere (mainly water vapour) in channel i , measured in percentage, $\alpha_i = \varepsilon_i \tau_i \cos(\theta)$, $\beta_i = k_i [1 + 2\tau_i (1 - \varepsilon_i) \cos(\theta)]$, $L_i = T_i / n_i$ in which n_i is a constant given in equation (12) for channel i , and τ_i is the atmospheric transmittance in channel i .

Compared to the algorithms given by Price (1984) and Coll *et al.* (1994a), this algorithm directly relates both coefficients A and B to the effects of atmospheric conditions and ground emissivity. In Price (1984) only atmospheric effects are considered for coefficient A and in Coll *et al.* (1994a) only coefficient B is related to the both effects.

Based on their radiation transfer equation (13) and simplification to the atmospheric effects, França and Cracknell (1994) also developed a split-window algorithm for retrieval of LST. The algorithm has the general form as equation (17) with the two coefficients given as follows:

$$A = (D_5 C_4 + D_4 C_5) / (D_5 C_4 - D_4 C_5) \quad (25)$$

$$B = \frac{(1 - \varepsilon_4)(1 - 2W_4)L_4 D_5 C_4}{\varepsilon_4 (D_5 C_4 - D_4 C_5)} - \frac{(1 - \varepsilon_5)(1 - 2W_5)L_5 D_4 C_5}{\varepsilon_5 (D_5 C_4 - D_4 C_5)} \quad (26)$$

where $C_i = \varepsilon_i \tau_i(\theta) \cos(\theta)$ and $D_i = W_i [1 + 2(1 - \varepsilon_i) \tau_i(\theta) \cos(\theta)]$, in which W_i is defined in equation (14). This algorithm is very similar to that of Sobrino *et al.* (1991). Actually, C_i in (25) and (26) is the same as α_i in (23) and (24). The only difference

between them is that the viewing angle is considered for atmospheric transmittance in C_i while that is not in α_i . D_i in (25) and (26) is also almost the same as β_i in (23) and (24). The difference between D_i and β_i is in the atmospheric parameter used for estimating them. The parameter used for D_i is W_i , a function of water vapour in the atmosphere, while that for β_i is k_i , the absorption coefficient of the atmosphere. Thus, it can be concluded that equations (25) and (26) are almost the same as (23) and (24).

Using the parameters A_0 , P and M given by Becker and Li (1990), Sobrino and Caselles (1991) proposed a simplified algorithm with the two coefficients A and B as:

$$A = (M - P)/2 \quad (27)$$

$$B = A_0 + T_4(P - 1) \quad (28)$$

where the parameters A_0 , P and M have been calculated by Becker and Li (1990) as:

$$A_0 = 1.274$$

$$P = 1 + 0.15616(1 - \varepsilon)/\varepsilon - 0.482\Delta\varepsilon/\varepsilon^2 \quad (29)$$

$$M = 6.26 + 3.98(1 - \varepsilon)/\varepsilon + 38.33\Delta\varepsilon/\varepsilon^2 \quad (30)$$

in which $\varepsilon = (\varepsilon_4 + \varepsilon_5)/2$ and $\Delta\varepsilon = \varepsilon_4 - \varepsilon_5$. From equations (27)–(30), we can see that the important coefficients A and B in the algorithm proposed by Sobrino and Caselles (1991) are directly expressed as the functions of surface emissivity in channels 4 and 5. It seems that the effects of atmospheric conditions are expressed as constants. This emphasis is quite different from that of Price (1984), Coll *et al.* (1994a), Sobrino *et al.* (1991) and França and Cracknell (1994), which emphasize the effects of atmosphere in the calculation of coefficients A and B .

Therefore, using equation (17) with the two coefficients, theoretically, it should be possible to retrieve the true surface temperature if the total atmospheric transmittance τ_i , the total water vapour content w for a given atmospheric state and ε_4 and ε_5 of the surface are known. However, the detailed data for these variables are usually not available *in situ* the satellite sensor observing the thermal radiance. Thus, the method for estimating the coefficients A and B is usually based on the simulation data given by running the LOWTRAN 7 program for a standard atmospheric profile (Sobrino *et al.* 1991, Coll *et al.* 1994a, França and Cracknell 1994).

3.2. Other forms of split-window algorithm

Apart from the general form of equation (17), other forms of the split-window algorithm for the retrieval of LST from AVHRR data also have been proposed by different scholars in the last decades (Badenas and Caselles 1992, Norman *et al.* 1995, Vogt 1996). The algorithm given by Becker and Li (1990) is worthy of detailed description since it has been cited in many papers (França and Cracknell 1994, Givri 1995) on the study of LST. Becker and Li (1990) presented a local split-window algorithm for viewing angles of up to 46° from nadir, given as follows:

$$T_s = A_0 + P(T_4 + T_5)/2 + M(T_4 - T_5)/2 \quad (31)$$

where A_0 , P and M are coefficients influenced by a number of factors in the process of radiance transmission from the ground to the sensor. For AVHRR data, coefficient $A_0 = 1.274$ and P and M are determined by equations (27) and (28). Later Becker and Li (1995) modified their algorithm into a general one keeping the form of equation (31). The only difference in the modified algorithm is that the coefficients

are determined in terms of water content calculated from radiance simulation using the LOWTRAN 7 program (Caselles *et al.* 1997).

Based on Becker and Li (1990), a generalized split-window algorithm has been developed by Wan and Dozier (1996). The form of algorithm is the same as equation (32) but the coefficients P and M are given as follows:

$$P = A_1 + A_2 \Delta \epsilon \epsilon^2 + A_3 (1 - \epsilon) \epsilon \quad (32)$$

$$M = B_1 + B_2 \Delta \epsilon \epsilon^2 + B_3 (1 - \epsilon) \epsilon \quad (33)$$

where $A_1 \sim A_3$ and $B_1 \sim B_3$ are parameters estimated by the method given by Becker and Li (1990). The difference is that Wan and Dozier (1996) defined A_1 in their model as a variable while Becker and Li (1990) defined it as a constant equal to 1. Similarly, the parameters are determined by regression analysis of the brightness temperature data to the simulated ground data of standard atmosphere given by the LOWTRAN 7 program, based on many assumptions on such variables as atmospheric state and viewing angles. Wan and Dozier (1996) compared the error of the generalized algorithm by the viewing angle θ -independent and θ -dependent methods. Simulation shows that the θ -dependent method is better than the θ -independent one. By using the θ -dependent algorithm, the variation in the atmospheric column water vapour is separated from the optical path change with respect to viewing angle so that the accuracy of surface temperature retrieval is improved. The algorithm can give an accuracy of 1 K in LST retrieval. Although a procedure has been established by Wan and Dozier (1996) for the θ -dependent methods, the details of how to determine the parameters and their empirical solution for the retrieval of LST from AVHRR data are not given.

Ottlé and Vidal-Madjar (1992) also presented a split-window algorithm for retrieving LST from channels 4 and 5 of AVHRR data, by using a linear relationship between LST and brightness temperature as follows:

$$T_s = a_0 + a_1 T_4 + a_2 T_5 \quad (34)$$

where a_0 , a_1 and a_2 are coefficients representing the total effects of the atmospheric conditions and the impact of ground surface emissivity. It is well known that LST is extremely variable in space. Even within a distance of 1 m, an obvious difference can be obtained to the surface temperature and near surface temperature. Moreover, it is not a simple matter to average ground data (if available) at the satellite pixel scale. In order to estimate the coefficients of the above linear equation, the 1207 atmospheric situations from the Automated Atmospheric Absorption Atlas have been considered by Ottlé and Vidal-Madjar (1992) for the three general air masses: tropical, mid-latitude and polar systems. Regressions were computed for each possible viewing angle so that the coefficients of the equation can be determined in relation to the variation of the viewing angles. Table 2 presents the results for the mid-latitude atmosphere with different viewing angles, by assuming that the surface behaves like a perfect black body in the two spectral bands. Ottlé and Vidal-Madjar (1992) noticed from the result that the scan angle has little influence on the coefficient value of the algorithm and that the root mean square (rms.) error on LST retrieval is very small in all the cases, increasing very slowly with angle.

It is well known that the radiance of thermal wavebands is strongly affected by surface emissivity, which prevents the direct use of the split window coefficients over land. Keeping in mind that viewing angle has little effect on the coefficients, Ottlé

Table 2. Coefficients of the AVHRR split-window algorithm for different viewing angles (after Ottlé and Vidal-Madjar 1992).

Angle (°)	Coefficients			rms. error (K)
	a_0	a_1	a_2	
0.0	0.858	3.218	- 2.218	0.123
9.0	0.854	3.225	- 2.225	0.123
16.0	0.833	3.230	- 2.231	0.128
23.0	0.852	3.258	- 2.258	0.135
32.0	0.880	3.289	- 2.290	0.145
38.0	0.924	3.328	- 2.329	0.158
44.0	0.928	3.372	- 2.372	0.174
48.0	0.910	3.409	- 2.410	0.189
53.0	0.929	3.468	- 2.469	0.211

and Vidal-Madjar (1992) analysed the effect of surface emissivity on LST retrieval. In the first step, the surface emissivity has been assumed to be the same in the infrared channels of AVHRR so that the general effect of emissivity can be clearly shown. The result of the analysis is listed in table 3. Ottlé and Vidal-Madjar (1992) found that an error of 2% on the mean value of ground emissivity ($\delta\varepsilon=2\%$) could yield an error of 1 K on the estimated LST ($\delta T=1$ K). This is much better than what Becker (1987) estimated $\delta T=1$ K for $\delta\varepsilon=1\%$. However, the scan angle has a slightly greater effect on the coefficients and the rms. errors decrease a little for lower values of emissivity.

Generally, the ground emissivity can be assumed to be 0.96–0.98 for most situations. In the second step, Ottlé and Vidal-Madjar (1992) evaluated the effect of emissivity difference between channels 4 and 5 of AVHRR data on the estimation of the coefficients in equation (34) using simulation data. Table 4 shows the result of the simulation, which shows that the effect of the spectral variation of the surface emissivity on the split-window algorithm increases with the value of the scan angle in all cases. For an error of emissivity difference $\delta(\Delta\varepsilon)=2\%$, δT is about 1.5 K for nadir view and 2.5 K for the viewing angle of 53°. When using $\delta(\Delta\varepsilon)=1\%$, they got δT to be about 1 K for the same conditions as used by Becker (1987), who predicted $\delta T=2.5$ K for $\delta(\Delta\varepsilon)=1\%$.

Table 3. Coefficients of the AVHRR split-window algorithm for different viewing angles and mean emissivity (after Ottlé and Vidal-Madjar 1992).

Mean emissivity	Angle θ	Coefficients			rms error (K)
		a_0	a_1	a_2	
1.0	0	0.859	3.218	- 2.218	0.123
1.0	53.0	0.929	3.468	- 2.469	0.211
0.98	0	- 0.403	3.219	- 2.211	0.111
0.98	53.0	- 0.418	3.506	- 2.499	0.201
0.96	0	- 1.687	3.213	- 2.197	0.102
0.96	53.0	- 1.761	3.487	- 2.471	0.184
0.94	0	- 2.889	3.214	- 2.190	0.097
0.94	53.0	3.151	3.524	- 2.499	0.178

Table 4. Coefficients of the AVHRR split-window algorithm for different viewing angles and different emissivity in the two channels 4 and 5 of the AVHRR (after Ottlé and Vidal-Madjar 1992).

Emissivity	θ	a_0	a_1	a_2	rms. error (K)
$\varepsilon_4 = 0.98$	0	-0.502	3.023	-2.013	0.116
$\varepsilon_5 = 0.985$	53	-0.515	3.349	-2.339	0.201
$\varepsilon_4 = 0.96$	0	-2.186	2.444	-1.420	0.173
$\varepsilon_5 = 0.98$	53	-2.239	2.830	-1.804	0.250
$\varepsilon_4 = 0.98$	0	-1.301	2.510	-1.492	0.161
$\varepsilon_5 = 1.00$	53	-1.368	2.901	-1.881	0.239

Kerr *et al.* (1992) also proposed an algorithm for retrieval of LST in semi-arid and arid environments. The algorithm is similar to equation (34). They considered the surface in arid and semi-arid environment to be composed of vegetation coverage and the bare soil though vegetation coverage is sparse. According to equation (34), the surface temperatures of vegetation canopy, T_v , and bare soil, T_{bs} , can be estimated.

The LST in the environment is the function of T_v and T_{bs} according to the following formula:

$$T_s = CT_v + (1 - C)T_{bs} \quad (35)$$

where C is a fractional coefficient of vegetation coverage in semi-arid and arid environment, which can be derived from Normalized Difference Vegetation Index (NDVI) values with the expression (Kerr *et al.* 1992):

$$C = (\text{NDVI} - \text{NDVI}_{bs}) / (\text{NDVI}_v - \text{NDVI}_{bs}) \quad (36)$$

where NDVI_{bs} is the minimum value of the NDVI for bare soil over the region of interest and NDVI_v correspond to the highest NDVI expected for a fully vegetated pixel. The unique characteristic of this algorithm is that it divides the surface into two typical patterns and considers their various contributions to the LST in the pixel scale, while other algorithms view the surface as one pattern. Another unique feature is that this algorithm directly relates the LST to the NDVI, an important index measuring vegetation of the ground surface.

The algorithm presented by Kerr *et al.* (1992) has been tested and validated over two test sites. One is located in the south-east of France (Caumont near Avignon 43° 54' N, 4° 51' E) and the other is in Niger in Dangurey Gourou (13° 59' N, 2° E) near Niamey. They obtained the empirical solution of the coefficients in equation (35) as follows:

Surface patterns	a_0	a_1	a_2
Bare soil	3.1	3.1	-2.1
Vegetation	-2.4	3.6	-2.6

For the fractional coefficient C they used $\text{NDVI}_{bs} = 0.11$ and $\text{NDVI}_v = 0.72$. The result shows that the algorithm fit rather well with the measured data. The difference between the estimated LST and the measured LST has a mean value of -0.25 K and a standard deviation of 0.9 K (Kerr *et al.* 1992). This accuracy is much better than the general accepted error 1.5 K. Because arid land environment is the most

difficult case for split-window technique, Kerr *et al.* (1992) believed that this algorithm can give a better result for other land surfaces.

4. Effect of ground emissivity on retrieval of LST

When applying the split-window algorithm to retrieve LST from AVHRR data, one potential complication arises from the possible effects of emissivity variation of natural surfaces in the thermal window. The derivation of many algorithms for LST is based on the assumption that the ground surface acts as a black body with $\varepsilon=1$.

Actually, the Earth's surface is not a black body, which means that its emissivity is less than 1. All real materials emit only a fraction of the energy emitted by a black body at the same temperature. Therefore, the thermal radiance received by the sensors on board satellite is also determined by surface emissivity (Barducci and Pippi 1996). The emitting ability of a ground object, compared to that of a black body, is referred to as the object's emissivity, which describes how efficiently the object radiates energy compared to a black body. When using AVHRR data to calculate LST, it is important to know the emissivity of the surface sensed and how it affects the LST.

4.1. Emissivity correction to split-window algorithms

For the application of split-window algorithm to land surface temperature retrieval, Becker (1987) evaluated the possible error δT of LST estimation generated by the surface emissivity as follows:

$$\delta T \cong 50(1 - \varepsilon) \Delta \varepsilon - 300 \Delta \varepsilon \varepsilon \quad (37)$$

where $\Delta \varepsilon = \varepsilon_4 - \varepsilon_5$ is the difference of ground emissivity in the two AVHRR channels. Assuming the average emissivity to be $\varepsilon = 0.96$ and the difference of emissivity, $\Delta \varepsilon$, to be 0.002, the probable error of retrieved LST would be 1.4583 K. Therefore, the LST estimation error δT may be quite significant when the ground surface is obvious heterogeneity on the region studied. And this is usually the case for natural surfaces.

Li and Becker (1993) predicted the impact of surface emissivity error on the estimation error of LST as follows:

$$\delta T \cong -52 \delta \varepsilon - 110 \delta(\Delta \varepsilon) \quad (38)$$

where $\delta \varepsilon$ donates the error of average emissivity and $\delta(\Delta \varepsilon)$ donates the error of emissivity difference between channels 4 and 5. If $\delta \varepsilon = \delta(\Delta \varepsilon) = 0.01 = 1\%$, the LST estimation error δT is larger than 1.6 K. Therefore, it is necessary to have a good knowledge of surface emissivity in order to use split-window algorithm for retrieval of LST from AVHRR data.

The surfaces in agricultural areas have an average emissivity of $\varepsilon = 0.97$ in the thermal spectral interval 10.8–11.9 μm and a value of 0.96 may be assumed for most of the land surface and vegetation cover (Price 1984). According to the relation between emissivity and the temperature, after accounting for the effect of surface emissivity variation, Price (1984) calibrated his algorithm as follows:

$$T_s = [T_4 + 3.33(T_4 - T_5)] \left[\frac{5.5 + \varepsilon_4}{4.5} \right] + 0.75 T_5 (\varepsilon_4 - \varepsilon_5) \quad (39)$$

All temperatures are measured in K. Thus, at the Earth's ambient temperature of 300 K, an emissivity difference of 0.01 between the two channels may causes a change of 2 K in LST estimation.

Compared to Price (1984), Coll *et al.* (1994a) considered the effect of ground emissivity only in the coefficient B of their algorithm. Other algorithms such as Sobrino *et al.* (1991) and França and Cracknell (1994) directly relate the determination of both coefficients A and B to ground emissivity. In the algorithm presented by Becker and Li (1990) and Wan and Dozier (1996), ground emissivity is also a key factor for determining the required coefficients. Therefore, ground emissivity is very important for the accuracy of LST retrieval from AVHRR data.

4.2. Emissivity of the main ground surface objects

Different materials have different emissivity in the thermal band. Table 5 lists the emissivity of some typical materials in the thermal band 8–14 μm at the ambient temperature of the Earth, 300 K. Another feature of ground surface emissivity is that it is not a constant for all wavelengths. The emissivity of the ground surface has slight differences in the various thermal channels of satellite sensors. For AVHRR data, the surface emissivities of channels 4 and 5 usually have a difference of 0.002–0.005, which has been shown to be significant for the accuracy of LST retrieval (Li and Becker 1993). Thus, once the surface's emissivity of the thermal channels are known, the surface temperature can be determined by using a split-window algorithm. However, the surface emissivity for a large area is usually not available *in situ* during the satellite pass. Furthermore, it is also very difficult to directly measure the emissivity. Consequently, as we have seen in the above description, some researchers assumed a given emissivity for simplification in the derivation of their split-window algorithm (Price 1984). For the thermal spectral region, the ground surface is usually assumed to be an almost black body with emissivity in the range of 0.96–0.98.

By field experimental measurements, Labeled and Stoll (1991a,b) studied the variability of land surface emissivity in the thermal infrared band and the effect of surface emissivity on temperature. For the field measurement of emissivity, a box methodology has been established in order to control environmental radiation and to avoid a direct surface temperature measurement. The ideal place for the experiment is a natural surface which can be classified as stony area with different material composition: clay accounts for 22.98% of the total measured area, silt for 24.05%, coarse silt 6.41% and sands 46.55%. Different measurements have been done for the analysis of the measurement error (Labeled and Stoll 1991b). Experimental results show that the rms. of ground emissivity in the 8–14 μm thermal waveband is 0.959 with a standard deviation of 7.5×10^{-3} . The 8–14 μm emissivity of various vegetation cover types also has been calculated and the experimental results shown in

Table 5. Emissivity of some materials at the thermal band (after Lillesand and Kiefer 1987 and Sabins 1986).

Materials	Emissivity	Materials	Emissivity
Sea water	0.98	wood	0.90
Ice	0.96	granitic rock	0.89
Snow	0.85	silicon sandstone, polished	0.909
Wet soil	0.95	dolomite, polished	0.929
Dry soil	0.92	dolomite, rough	0.958
Sand	0.91	balsalt, rough	0.934
Tree leaves	0.96	feldspar	0.870

table 6 illustrate rapid increase of emissivity with vegetation height and density (Labeled and Stoll 1991b).

According to their experiments, Labeled and Stoll (1991b) gave the ground emissivity of channels 4 and 5 of the AVHRR as $\varepsilon_4 = 0.957$ and $\varepsilon_5 = 0.967$ for retrieving LST of La Crau region, southern France. Humes *et al.* (1994) summarized the reported ground surface emissivity in the 8–14 μm band, as shown in table 7.

Bare soil and canopy are the two most important surface types of the ground. In arid and semi-arid environments, bare soil usually dominates the ground surface by accounting for up to 80% of the total surface area while the vegetation canopy only occupies about 20% or less of the ground. Therefore, soil emissivity plays a more important role in retrieving the ground surface temperature in such environments. However, soil emissivity is highly variable as a function of soil composition and soil moisture. Studies indicate that the value of soil emissivity ranges from 0.84 to 0.98, while canopy emissivity ranges only from 0.94 to 0.99 and a saturation canopy may have an emissivity of up to 0.98–1.0 (Oliosio 1995). For agricultural areas where vegetation canopies dominate, leaf emissivity variations may introduce an error of as large as 1.5 K in retrieving LST from the observed radiance in the 10.5–12.5 μm window.

The ground emissivities shown in table 7 are not sufficient for accurate estimation of LST from AVHRR data. For specific studied region, ground emissivity should be calculated before applying split-window algorithm to retrieve LST from AVHRR data.

4.3. Methods for determining the ground emissivity for retrieval of LST

Experiments had been done by Humes *et al.* (1994) for computing ground surface emissivity. They used the ‘cone method’ for acquiring data of apparent temperature, T_{rad} , surface kinetic temperature, T_{kin} , and sky temperature, T_{sky} . Then, Planck’s

Table 6. The 8–14 μm emissivity of various vegetation cover types (Labeled and Stoll 1991b).

Vegetation cover types	Infrared emissivity
Very short grass	0.979
Tufts of grass (few cm)	0.981
Grassland (≈ 15 cm)	0.983
Rushes (≈ 100 cm)	0.994

Table 7. Reported ground surface emissivity in the 8–14 μm band for different surface types (Humes *et al.* 1994).

Ground surface types	Emissivity in 8–14 μm
Bare soil (sandy)	0.93
Bare soil (loamy sand)	0.914
Stony area	0.959
Grass (partial cover)	0.956
Shrub (partial cover)	0.976
Shrubs (complete cover)	0.986

equation was used to convert the three temperatures into the emittances M_{rad} , M_{kin} and M_{sky} . The relationship among the three emittance values can be expressed as

$$M_{rad} = \varepsilon M_{kin} + (1 - \varepsilon) M_{sky} \quad (40)$$

When solved for the surface emissivity, ε , equation (40) gives the expression

$$\varepsilon = \frac{M_{rad} - M_{sky}}{M_{kin} - M_{sky}} \quad (41)$$

Humes *et al.* (1994) measured various surfaces for estimating ground emissivity in the thermal infrared band. Their computation with a total of 183 experimental samples gives the results of the mean emissivity of bare soil rocks as 0.959, shrub and clumsy vegetation, 0.994 and rock/soil vegetation mixtures, 0.981.

Surface emissivity in channels 4 and 5 must be calculated for determining the coefficients of split-window algorithms such as Coll *et al.* (1994a), Sobrino *et al.* (1991), Sobrino and Caselles (1991) and Becker and Li (1990) and the calibration of the algorithms such as Price (1984). However, the appropriate filters of the radiometers for channels 4 and 5 are generally not available for the field data measurement. By using the field radiometers operating in the 8–14 μm wavelength region, a methodology has been created by Sobrino and Caselles (1991) to calculate the emissivity correlation of the AVHRR channels 4 and 5 as $\varepsilon_5 = \varepsilon_{8-14} + 0.001$, $\varepsilon_4 = \varepsilon_{8-14} - 0.003$ and $\Delta\varepsilon = \varepsilon_5 - \varepsilon_4 = 0.004 \pm 0.002$. Sobrino and Caselles (1991) experimented on several ground surfaces for computing ground emissivity in the 8–14 μm range and its relationship to the emissivity in channels 4 and 5 (table 8).

Therefore, knowledge of surface emissivity in thermal channels is important for estimating LST. Using the power law relation between radiance I_i and temperature given in equation (12): $I_i(T_i) = B_i(T_i) = c_i T_i^{n_i}$, Schmugge *et al.* (1991) provided a simple way to calculate the approximate surface emissivity. Actually, $B_i(T_i) = \varepsilon_i B_i(T_s)$. Thus, taking the ratio of the two channels 4 and 5, one can obtain

$$\varepsilon_5 = \frac{n_5^{n_4}}{\varepsilon_4^{n_5/m_4}} (T_5/T_4)^{n_5} \quad (42)$$

For the same type of surface in an image, the emissivity ε_i may be relatively constant, but a large amount of variation of surface temperature T_s may exist which leads to the variation of brightness temperature T_i at the ground. By summing over m pixels for an average value of brightness temperature, equation (42) can be used to estimate the emissivity for channel 5 when the surface emissivity of channel 4 is given. Thus, by simulating with approximate emissivity in channel 4, equation (42) can be used to estimate the emissivity difference of the two channels for retrieving LST.

It is well known that, in channel 3 of AVHRR data which is located around

Table 8. Emissivity values for different ground surfaces in the 8–14 μm waveband and AVHRR channels 4 and 5 (after Sobrino and Caselles 1991).

Ground surfaces	ε_{8-14}	ε_4	ε_5	$\Delta\varepsilon = \varepsilon_5 - \varepsilon_4$
Loam	0.951	0.972	0.983	0.011
Organic loam	0.942	0.973	0.978	0.005
Sand (SiO_2)	0.891	0.956	0.964	0.008
Sand (Niger)	0.913	0.967		
Caly (Niger)	0.965	0.980		
Kaolinite (pure)		0.984	0.979	-0.005

3.7 μm , the radiance emitted by the land surface itself and the reflected radiance due to sun irradiation during the day are of the same order of magnitude. Using this very interesting property, Li and Becker (1993) proposed a method for determining surface emissivity from AVHRR data using only the sun as an active source. The general idea behind this method is that the emitted radiance during the night can be used to evaluate the emitted radiance during the day, thanks to the temperature-independent spectral indices ($TISI$), which are defined by Li and Becker (1993) as follows:

$$TISI_n = M_c \frac{B_3(T_{g3n})}{B_4(T_{g4n})^{m_c} B_5(T_{g5n})} \quad (43)$$

$$TISI_d = M_c \frac{B_3(T_{g3d})}{B_4(T_{g4d})^{m_c} B_5(T_{g5d})} \quad (44)$$

where n and d refer to night and day, respectively. Thus, $B_3(T_{g3n})$ represents the Planck's function in channel 3 with the ground temperature T_{g3n} during the night. M_c and m_c are constants that have been determined according to the procedure explained in Becker and Li (1990a). For AVHRR of NOAA-11, the two constants have the values of $M_c = 0.62105 \times 10^{-7}$ and $m_c = 1.924$. Following several complex logical derivations and approximation assumptions, the ground surface emissivities in channels 4 and 5 of AVHRR can be calculated using the following formula:

$$\varepsilon = \left\{ \frac{\varepsilon(\theta)}{TISI_{54n} TISI_n} \right\}^2 \quad (45)$$

$$\varepsilon = \varepsilon_a^{p_{54}} TISI_{54n} \quad (46)$$

where p_{54} and p are constants with $p_{54} = 0.913$ and $p = 1/(p_{54} + m_c) = 1/2.837 = 0.352485$, $TISI_{54n}$ is a parameter which is determined according to the procedure given in Becker and Li (1990a), and

$$\varepsilon(\theta) = 1 - \left\{ \pi \frac{(TISI_d - TISI_n) B_4(T_{g4d})^{m_c} B_5(T_{g5d})}{M_c R_{g3}(\theta') \cos(\theta') f_3(\theta', \theta)} \right\} \quad (47)$$

where $R_{g3}(\theta')$ is the solar irradiance on the surface in channel 3 at zenith angle θ' , $f_3(\theta', \theta)$ is the angular form factor of the surface which is determined by the bi-directional reflectivity of the surface in channel 3 at θ and θ' (Li and Becker 1993). Therefore, the ground emissivity in channels 4 and 5 can be directly retrieved from space, provided that $R_{g3}(\theta')$ and $f_3(\theta', \theta)$ are known. For simplification, the ground surface can be assumed as a Lambertian body so that the angular form factor $f_3(\theta', \theta)$ can be defined as $f_3(\theta', \theta) = 1$. The solar irradiance $R_{g3}(\theta')$ can be calculated as

$$R_{g3}(\theta') = (\alpha/2)^2 \pi \int_0^\infty N_3(\lambda) B_\lambda(T_k) \tau_\lambda(\theta') d\lambda \cong R_{\tau_3}(\theta') \quad (48)$$

where $N_3(\lambda)$ is the spectral response in channel 3 of the radiometer of AVHRR; α is the solar apparent diameter with $\alpha = 9.3 \times 10^{-3}$, $\tau_\lambda(\theta')$ and $\tau_3(\theta')$ are the total atmospheric transmittances in wavelength λ and channel 3, respectively, at θ' , which can be estimated by simulation with the LOWTRAN 7 program; T_k is the solar temperature with $T_k = 5784 \text{ K}$; R is a constant with $R = 0.415536 \times 10^{-6} \pi$.

A method for estimating the difference between the two channel emissivities has been proposed by Coll *et al.* (1994b). The method is based on the separation between

the atmospheric and emissivity effects on the brightness temperature difference measured with AVHRR channels 4 and 5. Taking into account the several approximations for the radiance transfer of thermal energy, Coll *et al.* (1994b) found that the difference between the true surface temperature, T_s , and the brightness temperature, T_i , at surface level can be written as

$$T_s - T_i = \frac{1 - \varepsilon_i}{\varepsilon_i} b_i \quad (49)$$

where b_i is a parameter in units of temperature and can be given by equation (11). Applying equation (49) to channels 4 and 5, and eliminating T_s from the equation system, the following equation is obtained:

$$T_4 - T_5 = \frac{1 - \varepsilon_5}{\varepsilon_5} b_5 - \frac{1 - \varepsilon_4}{\varepsilon_4} b_4 \quad (50)$$

This relates the difference between the atmospherically corrected temperatures to the surface emissivity in both channels. When ε_i is close to 1 as is the case in the thermal window 10.5~12.5 μm for most natural surfaces, the above equation can be further simplified by using $\varepsilon_5 = \varepsilon_4 - \Delta\varepsilon$ to give

$$T_4 - T_5 = (1 - \varepsilon_4)(b_5 - b_4) + \Delta\varepsilon b_5 \quad (51)$$

where $\Delta\varepsilon = \varepsilon_4 - \varepsilon_5$ represents the emissivity difference between the two channels. Solving equation (51) for $\Delta\varepsilon$, one can get

$$\Delta\varepsilon = [(T_4 - T_5) - (1 - \varepsilon_4)(b_5 - b_4)] / b_5 \quad (52)$$

which can be used to calculate the emissivity difference between channels 4 and 5, provided that *a priori* estimate of ε_4 is available, which is usually assumed to be 0.96–0.98 for natural surfaces.

Sensitivity analysis indicates that the total error in $\Delta\varepsilon$ by using this method is about 0.004 (Coll *et al.* 1994b). This accuracy is sufficient for most LST applications, since the corresponding error in LST estimation is less than 1 K when the general form split window method with coefficients A and B given by equations (20) and (21) is employed.

Coll *et al.* (1994b) applied this method to real data in an experiment in southern France. They used the radiosonde profile of the experiment performed in June 1992 to calculate the required atmospheric parameters. Consequently the coefficients b_i and the emissivity differences $\Delta\varepsilon$ can be estimated, given that $\varepsilon_4 = 0.98$ for forest land in the experimental area. The result shown in table 9 indicates that the mean emissivity differences $\Delta\varepsilon$ is about 0.0081, which is higher than the general assumption $\Delta\varepsilon = 0.002$ for LST estimation. Thus, the emissivity difference $\Delta\varepsilon$ has to be computed for achieving a good accuracy of LST retrieval using split-window algorithm.

5. Conclusion

Land surface temperature determination has been an important area of remote sensing. Based on the thermal spectral radiation and atmospheric transmission information, many efforts have been devoted to the study of LST from remote sensing data. The retrieval of LST from AVHRR channels 4 and 5 have been extensively applied to different research purposes (Seguin 1996, Vogt 1996). First, the brightness temperature of the two channels is calculated by reversing Planck's function, then a split-window algorithm can be employed to retrieve the real LST.

Table 9. Atmospheric parameters and the emissivity difference in southern France (after Coll *et al.* 1994b).

DOY	γ_4	γ_5	$\tau_4(0^\circ)$	$\tau_5(0^\circ)$	$T_{a4} \downarrow (\text{K})$	$T_{a5} \downarrow (\text{K})$	$b_4 (\text{K})$	$b_5 (\text{K})$	$\Delta \varepsilon$
164	1.517	1.442	0.763	0.682	284.25	285.00	47.14	44.96	0.0081
166	1.479	1.394	0.704	0.604	289.55	290.42	44.59	40.94	0.0106
167	1.508	1.432	0.751	0.666	289.56	290.35	47.88	45.05	0.0228
170	1.471	1.385	0.696	0.593	291.96	292.77	43.88	40.01	0.0079
174	1.537	1.469	0.794	0.724	284.83	285.66	49.02	47.64	0.0088
191	1.497	1.420	0.739	0.650	289.08	289.73	46.22	43.47	0.0059
Mean	1.517	1.442	0.763	0.682	284.25	285.00	47.14	44.96	0.0081

DOY = day of the year.

After Price (1984), various split-window algorithms have been established for LST estimation. The most popular form of the algorithm is $T_s = T_4 + A(T_4 - T_5) + B$ though some other forms such as linear ones also have been used. However, the determination of coefficients A and B has great difference among various algorithms, in terms of the detailed derivations of the algorithms from the approximate assumptions to the different conditions and factors involved. Some algorithms (Coll *et al.* 1994a, França and Cracknell 1994) employ complex calculation formulae for coefficients A and B in order to gain accurate results. Others neglect some effects of the atmosphere and simplify the calculation of the two coefficients. Price (1984) assumed ground surface as black body for the derivation of his algorithms. Coll *et al.* (1994a) considered coefficient A as the function of only atmospheric effect. Sobrino *et al.* (1991) and França and Cracknell (1994) directly considered the effects of both atmosphere and ground emissivity in the derivation of their split-window algorithms. Becker and Li (1990) treated atmospheric effects as constant and only emphasized the ground emissivity in calculating the coefficients of their algorithm. Kerr *et al.* (1992) related NDVI to the estimation of LST according to the surface fraction of vegetation coverage in the pixel scale. These algorithms represent the main stream of methodology used to retrieve LST from the thermal channels of AVHRR data in remote sensing.

Actually, there are a number of factors affecting the coefficients of the split-window algorithm. However, the data of many factors involved are not available *in situ* satellite pass, leading to difficulties in applying some accurate but complex calculation methods to the retrieval of LST for specific regions. Therefore, it is concluded that, regardless of difference and complexity of various algorithms, usually only two approaches have been used to determine the coefficients: ground data calibration and standard atmospheric state simulation.

For the ground data calibration, it is assumed that coefficients result from the impacts of many known and unknown factors involved. The detailed mechanism of these factors' functioning may not be known but their functional results are known, i.e., the ground data measurements obtained as a sample of the total region studied *in situ* satellite pass. Therefore, by correlating the ground data measurements to the sample of the brightness temperatures in the two channels, one can get the coefficients for the algorithm. Then, the coefficients from the samples can be used to derive the LST of the whole image. This is relatively simple, but one difficulty is how to get a sample representing the ground data measurements at the pixel scale *in situ* satellite pass because there is great variation of LST over a small surface area.

Special programs have been developed for simulating the effects of the atmosphere on radiation transmission. The most popular software is the LOWTRAN 7 program for providing standard atmospheric conditions. By using the software with several inputs, the effects of the atmosphere as a standard profile can be calculated.

Furthermore many atmospheric parameters such as atmospheric absorption coefficient can be derived from the simulation results for the studied area. Therefore, some complex calculation formulae can be used to determine the coefficients of split-window algorithm (Sobrino *et al.* 1991, Coll *et al.* 1994a, França and Cracknell 1994). However, this is only the idealized standard situation and the actual conditions of the real world change from time to time and from place to place. Therefore, the determination of actual atmospheric effects on the coefficients of split-window algorithm in the real world still needs to be studied further.

Apart from the effects of atmosphere, another important factor on the accuracy of LST retrieval is ground emissivity. Usually, the ground is not a black body that operates a full emission, and this is the problem for using split-window algorithm to retrieve LST. Furthermore, the ground surface is far from homogeneous. It is composed of different materials at the satellite pixel scale, which makes the consideration of emissivity in LST retrieval difficult.

In the thermal portion of the spectrum, the ground emissivity is close to 1 even though different components of surface materials have different emissivity values. For an approximate estimation, it is usual to assume a ground emissivity of 0.96 for the application of split-window algorithm. Actually, this is not true because different surfaces have different emissivity, which may range from 0.91 to 0.99. Furthermore, the ground emissivity is not equal, but slightly different in the two AVHRR channels. This difference has been proved to be very important for the accuracy of LST retrieval.

Various methods have been created to estimate ground emissivity and its difference in the two thermal channels (Becker and Li 1993, Coll *et al.* 1994b). Theoretically, the ground emissivity in channels 4 and 5 can be derived from the remote sensing data of AVHRR channels 3, 4 and 5 based on some assumptions. However, the method also involves a number of atmospheric parameters, which are generally difficult to determine because the needed data are usually not available *in situ* the satellite pass. Therefore, the estimation of ground emissivity also requires the standard atmosphere profile provided by the LOWTRAN program to simulate the effects of the potential factors involved. Studies indicate that the ground emissivity of channels 4 and 5 may have a difference ranging from 0.002 to 0.008 (Sobrino and Caselles 1991, Coll *et al.* 1994b).

As we can see, there are many aspects of the remote sensing of LST that need further study. In recent decades, it seems that the focus of the area has been on algorithms and their calibration. Almost all the papers published addressed the different aspects of LST retrieval algorithm itself. There seem to be few papers on the real application. Even though there are some studies that address the actual application of remote sensing to LST analysis, usually they only present some sample analysis and demonstration of the accuracy of LST estimation, but little is done about further examination of the LST regime itself. This phenomenon indicates that the application of remote sensing to LST in the real world still requires much study. Meanwhile, the coefficients in the proposed algorithms seem to be treated as relatively fixed for the whole image. This is not strictly true, especially when the image under study covers a vast region. It is well known that the factors impacting on thermal

transmission through the atmosphere behave obviously different from pixel to pixel. By using the relatively fixed coefficients for the retrieval of LST to the whole studied region, the difference will be omitted. In the case of the image covering a vast region, this may create significant errors in LST retrieval. Therefore, a spatially dynamic calibration model still needs to be developed for the real spatial distribution of LST.

Appendix. Notation

A, A_0	Coefficients of split-window algorithm in (17) and (31)
A_1, A_2, A_3	Parameters for calculating coefficient P in (32)
A_r	Parameter for calculating coefficient A in (18)
A_λ, A_4, A_5	Parameters representing atmospheric effects in wavelength λ , channels 4 and 5
a	Parameter in (15) and (16)
a_0, a_1, a_2	Coefficients of split-window algorithm in (36)
a_{1i}, a_{2i}	Parameters for calculating parameter W_i of (14)
B	Coefficient of split-window algorithm in (17), K
B_1, B_2, B_3	Parameters for calculating coefficient M in (33)
$B_\lambda(T)$	Planck's radiance at temperature T and wavelength λ , $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$
$B_i(T_{az})$	Atmospheric radiance in channel i at T_{az} of altitude z
$B_i(T_s), B_\lambda(T_s)$	Radiance of ground surface at temperature T_s in channel i and wavelength λ
$B_3(T_{g3n})$	Planck's radiance at ground temperature T_{g3n} in channel 3 at night
$B_4(T_{g4n})$	Planck's radiance at ground temperature T_{g4n} in channel 4 at night
$B_5(T_{g5n})$	Planck's radiance at ground temperature T_{g5n} in channel 5 at night
b_i, b_4, b_5	Parameters for channel i , 4 and 5 in (10), (11), (21), (50) and (51), K
C	Fraction of vegetation in (35) and (36)
C_i, C_4, C_5	Parameters for channels i , 4 and 5 in (29) and (30)
c	Speed of light, $c = 2.99792458 \times 10^8 \text{ m s}^{-1}$
c_i	Constant for channel i in (12)
c_1	Constant in (3), $c_1 = 2\pi hc^2 = 3.741771995 \times 10^{-16} \text{ W m}^2$
c_2	Constant in (3), $c_2 = hc/k = 1.43876869 \times 10^{-2} \text{ m K}$
D_i, D_4, D_5	Parameters for channels i , 4 and 5 in (29) and (30)
d_0, d_1	Constants in (22), $d_0 = 1.29$ and $d_1 = 0.28$
$f_3(\theta', \theta)$	Bi-directional reflectivity of the surface in channel 3
h	Planck's constant, $h = 6.626076 \times 10^{-34} \text{ J s}$
$I_i(T_i), I_\lambda(T_\lambda)$	Observed radiance at temperature T_i and T_λ in channel i and wavelength λ
I_0	Parameter in (15) and (16)
i	Channel of remote sensor
k	Boltzmann constant, $k = 1.380658 \times 10^{-23} \text{ J K}^{-1}$
k_i, k_λ	Absorption coefficients of the atmosphere in channel i and wavelength λ
L_i, L_4, L_5	Parameters for channel i , 4 and 5 in (14), (24) and (30)

$L_i^\uparrow(\theta)$	Upward radiance of the atmosphere at viewing angle θ
$L_i^\downarrow(\theta=0)$	Downward radiance of the atmosphere at nadir direction
M	Coefficient of split-window algorithm in (39)
M_{kin}	Emittance converted from kinetic temperature T_{kin} by Planck's equation
M_{rad}	Emittance converted from apparent temperature T_{rad} by Planck's equation
M_{sky}	Emittance converted from sky temperature T_{sky} by Planck's equation
M_c, m_c	Constants in (43) and (44), $M_c = 0.62105 \times 10^{-7}$ and $m_c = 1.924$
NDVI	Normalized Difference Vegetation Index
NDVI _{bs}	Minimum value of NDVI for bare soil in (37), NDVI _{bs} = 0.11
NDVI _v	The highest NDVI for a vegetated pixel in (37), NDVI _v = 0.78
$N_3(\lambda)$	Spectral response of the radiometer of AVHRR in channel 3
n_i, n_4, n_5	Constants for channel $i, 4$ and 5 in (11), (12) and (42)
P	Coefficient of split-window algorithm in (31)
p, p_{54}	Constants in (45) and (46), $p = 0.352485$ and $p_{54} = 0.913$
R	Constant in (48), $R = 0.415536 \times 10^{-6} \pi$
$R_{g3}(\theta')$	Solar irradiance on the ground surface in channel 3 at zenith direction θ'
T	Temperature of an object, K
$TISI_n, TISId$	Temperature independent spectral indices at night and day in (43)–(47)
T_a	Average atmospheric temperature, K
T_{ai}, T_{a4}, T_{a5}	Atmospheric temperatures in channels $i, 4$ and 5 , K
T_{az}	Atmospheric temperature at altitude z , K
T_{bs}	Surface temperature of bare soil in (36), K
$T_{g3n}, T_{g4n}, T_{g5n}$	Ground temperatures in channels 3, 4 and 5 at night, K
T_i, T_4, T_5	Brightness temperature in channels $i, 4$ and 5 , K
T_k	Solar temperature in (51), $T_k = 5784$ K
T_{kin}, T_{rad}	Kinetic and apparent temperature of the ground surface, K
T_s	Land surface temperature, K
T_{sky}	Sky temperature, K
T_v	Canopy surface temperature of vegetation in (36), K
T_0	Parameter in (15) and (16)
T_λ	Brightness temperature in wavelength λ , K
U_t	Atmospheric determinant at temperature T in (7)
W_i	Parameter representing the effect of water vapour in atmosphere
w	Water vapour content in the atmosphere, $g\ cm^{-2}$
Z	Altitude of the sensor from the ground, km
z	Average atmospheric altitude between ground and the sensor, km
$\Delta T_4, \Delta T_5$	Differences of brightness temperatures T_4 and T_5 to their averages, K
$\Delta \varepsilon$	Difference between emissivities of channels 4 and 5
α	Solar apparent diameter, $\alpha = 9.3 \times 10^{-3}$
$\alpha_i, \alpha_4, \alpha_5$	Parameters for channel $i, 4$ and 5 in (23) and (24)
$\beta_i, \beta_4, \beta_5$	Parameters for channel $i, 4$ and 5 in (23) and (24)
δT	Estimation error of LST, K

$\delta(\Delta\varepsilon)$	Estimation error of emissivity difference $\Delta\varepsilon$
ε	Average emissivity, $0 \leq \varepsilon \leq 1$
$\varepsilon_i, \varepsilon_4, \varepsilon_5$	Ground surface emissivities in channels $i, 4$ and 5
$\varepsilon_3(\theta)$	Ground surface emissivity in channel 3 at viewing angle θ
$\varepsilon_{8-14}, \varepsilon_\lambda$	Emissivities at wavelength $8-14 \mu\text{m}$ and λ
γ_i	Atmospheric parameter for channel i in (8)
λ	Wavelength, m
θ	Viewing angle of the remote sensor
θ'	Zenith angle of downward atmospheric radiance
τ_i, τ_4, τ_5	Atmospheric transmittances in channels $i, 4$ and 5
$\tau_i(\theta), \tau_4(\theta), \tau_5(\theta)$	Atmospheric transmittances in channel $i, 4$ and 5 at viewing angle θ
$\tau_i(\theta, z, Z)$	Atmospheric transmittance between altitude z and Z at viewing angle θ
$\tau'_i(\theta', z, 0)$	Atmospheric transmittance between z and the ground at zenith angle θ'
τ_λ	Optical thickness from the ground to the sensor at wavelength λ
τ'_λ	Optical thickness from average atmospheric height to the sensor
$\tau_\lambda(\theta'), \tau_3(\theta)$	Total atmospheric transmittances at wavelength λ and in channel 3 at θ'

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