A Brief Review of Land Surface Temperature Retrieval Methods from Thermal Satellite Sensors

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Abstract: Land surface temperature (LST) has a significant role in the land surface characters on local and global scale. The most important task in estimation of LST from satellite thermal data is removing the effects of atmospheric attenuations, topographic and land surface emissivity. To date, several techniques have been proposed to retrieve LST with various applications, advantages and drawbacks. This paper aims to provide a brief review of three most applied LST acquisition methods including single-channel technique, split-window technique and multi-angle technique. This paper first provides a detail of theoretical background of LST retrieval and then reviews published studies about single-channel; split-window and multi-angle techniques. This survey shows that, the split-window technique has become most applied technique in LST related studies compared to the single-channel and multi-angle techniques. Because, the accuracy of estimated LST using split-window technique due to its less need to precise atmospheric temperature and water vapor content is higher. However, some limitations is remained in using LST products from thermal sensors, such as a trade-off between spatial and temporal resolutions in thermal data and uncertainties in accurate LST acquisition, which makes it valuable topic to concern in future studies.

Key words: Land surface temperature (LST) · Atmospheric correction methods · Split-window technique · Single-channel · Multi-angle · Thermal sensors data

INTRODUCTION

In all correlations between land surface and atmosphere and energy fluxes with ground and the atmosphere, land surface temperature (LST) is a most significant factor, as well as a good index energy equilibrium on the ground surface, climatic and environmental studies [1-4]. For the exchange of energy between the surface and the atmosphere, the surface temperature is the principal controlling factor and for detailed local, regional and global numerical models of weather and climate, as well as many other applications, accurate measurements are need [5]. To retrieve LST from satellite Thermal Infrared (TIR) data many factors need to quantify, such as, radiometric and atmospheric calibrations, correction of surface emissivity, characterizing of spatial variability over land cover and the combination of effects of viewing geometry and fraction of cover vegetation. These factors are dependent on atmospheric conditions and emissivity of the land surface materials. Therefore, the effects of both atmosphere and land surface emissivity must be corrected for an accurate LST measurement [6].

There are many applications which are required accurate LST as input parameter such as drought, forest fire, monitoring of vegetation and climate studies and so on. Thus, acquiring LST from remotely sensed data becomes one of the significant factors in quantificational remote sensing study. To retrieval of the LST from spectrum region, the thermal infrared (TIR, 3-15 µm) and microwave bands (1 mm-1 m) are important regions [4]. Land surface is usually heterogeneous with different reflectance and absorption of solar energy, even for a small scale of the earth’s surface. The topography and type of vegetation cover have effect on the surface temperature. Remote sensing of land surface temperature (LST) using infrared radiation necessarily gives an average surface temperature of the scene covered by the radiometer’s field of view. This spatial variation in LST acquisition causes to decrease accuracy in
measurement and makes difficulty in validation of LST measurements from space with using in situ measurements [5]. The emissivity and reflectivity of object’s surface, temperature of atmosphere, distance of measurement and attenuation of atmosphere are cases which have direct effect on the measured LST accuracy with IR imagers [7]. Only by satellite-based measurements can provide LST information over large areas. The interaction between land surface and atmosphere is more complex.

Three factors have effects on the retrieval of accurate LST: 1) the effects of atmosphere in the infrared radiation transfer (e.g. water vapor and clouds); 2) coupling LST and land surface emissivity (LSE) make a complex situation to LST retrieval; 3) sensor type [8]. Satellites have spatial and temporal applications that they can monitor large and remote areas over an extended period of time. Generally, land surface temperature products are derived from thermal infrared (TIR) sensors (e.g. AVHRR, MODIS or METEOSAT). Among mentioned TIR sensors, the LST products of MODIS aboard the Terra and Aqua platforms data have high quality, global coverage and accurate geolocation. On the other hand, high quality calibrated TIR to LST retrieval, accurately is used [9, 10, 11].

Wei et al. [12] improved a split-window algorithm for retrieving land surface temperature from MODIS data. Hulley and Hook [13] compared two versions 4, 4.1 and 5 of the MODIS land surface temperature and emissivity products over arid and semi-arid areas. According to their lab results over desert regions, emissivities of V5 were higher than rates in all bands, although they may be more accurate and stable over water and vegetated areas.

Liu et al. [14] proposed an algorithm for LST and emissivity estimation from MODIS observations. The proposed algorithm is more suitable for a wide range of surface temperatures and surface type, compared with the TES algorithms. In addition, in using proposed algorithm no need to know a priori information about surface types. To other sensors with existing at least two TIR bands, for instance VIRR on board FY-3A, can apply this proposed algorithm. The RMSE of the retrieved LST using this algorithm is less than 1.0 K [15-17] investigated land surface temperature algorithms using NOAA AVHRR images. They found there is a principled discrepancy between the emissivity values. Serpico et al. [18] used support vector machines for LST estimation from passive satellite images. The results showed that when bands 4 and 5 of AVHRR data were applied LST estimation, the suggested method based on SVM can prepare good estimates of LST. The accuracies of classical unsupervised algorithms based on the split-window method were lower than obtained accuracies. Pinheiro et al. [19] developed a new daytime and nighttime LST over Africa using NOAA-14 AVHRR channel 4 and 5 during the period of 6 years. Their method applied for estimating of emissivity by [20].

A few of reviews exist about LST, these reviews have covered study of UHI by satellite remote sensing [21, 22], the theory and practice–current trends and limitations of LST retrieval [23] and TIR remote sensing [24-26]. This paper aims to provide a brief review of three most popular and applicable methods to LST retrieval (single-channel method, split-window method and multi-angle method).

Theory Background

The Act of the Atmosphere: In the atmosphere the energy comes from a primary solid angle per time unit and wavelength unit can be written as:

$$dI\lambda/d\Omega = (I_e + B_s)s$$  \hspace{1cm} (1)

where, $I_e$ is the intension of radiation at wavelength $\lambda$ crossing from a layer which has absorption and emission, $s$ is the length of direction, $B_s$ is the blackbody emissivity of the layer given by the Planck function and $\tau_s$ is the optical depth [25].

To retrieving LST must consider Planck’s function, which is related to emitted radiative energy from black body ($\varepsilon = 1$) to its temperature. But, most of the natural objects are not black bodies ($0 < \varepsilon(\lambda) < 1$). Planck’s function for non-black body object is multiplied by $\varepsilon(\lambda)$:

$$R(\lambda, T) = \varepsilon(\lambda)B(\lambda, T) = \varepsilon(\lambda)\frac{c_1\lambda^2}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}$$  \hspace{1cm} (2)

where, $B(\lambda, T)$ is black body spectral radiation (Wm$^{-2}$ µm$^{-1}$ sr$^{-1}$) (Planck’s function); $R(\lambda, T)$ is a non-black body spectral radiation (Wm$^{-2}$ µm$^{-1}$ sr$^{-1}$); $\lambda$ wavelength ($\mu m$); $\varepsilon(\lambda)$ spectral emissivity of a body at $\lambda$; T temperature (K); $c_1$, $c_2$ universal constants.

The Kirchoff’s law about radiation remarks a body is a good absorber and emitter:

$$\alpha(\lambda) = \varepsilon(\lambda)$$  \hspace{1cm} (3)

where, $\alpha(\lambda)$ is the absorption. If emissivity is recognized and upwelling radiance and reflected downwelling irradiance in the atmosphere are separated, the temperature of a Lambertian reflector can be determined by reversing equation (1):
Fig. 1: Distribution of radiated energy of blackbody at different spectral temperatures.

![Distribution of radiated energy of blackbody at different spectral temperatures.](image1)

The wavelength of blackbody radiation in the maximum point is depending on its temperature by Wien’s displacement law;

$$\lambda m = \frac{A}{T}$$  \hspace{1cm} (5)

where

- $\lambda$ = wavelength of maximum spectral radiant existence,
- $A = 2898 \, \mu m \, K$
- $T = \text{temperature, K}$

Figure 1 shows the distribution of radiated energy of blackbody at different spectral temperatures, the $M_\lambda$ is the emitted energy per unit wavelength interval. The sum radiation existence $M$ is given by the area under the spectral radiant existence curves.

To use LST measurements from EMR spectrum the thermal infrared (TIR) is most used section, which is located between 8-15 µm ranges (Figure 2).

Based on Planck’s law, for each temperature the maximum ratio of radiation which is emitted has own special wavelength $\lambda_m$. According Wien’s law the product of these temperatures (T) and the corresponding $\lambda_m$ is constant:

$$\lambda_mT = 2897.9 \, \mu m \, K$$  \hspace{1cm} (6)

For Earth with an ambience temperature around 300K, $\lambda_m$ located at 9.7 µm. Figure 2 shows Planck’s function for Earth-emitted radiation temperatures of 300K and reflection of solar irradiance from the Earth’s surface which is 6000K (Figure 3).

Suitable part for LST: Basic need for remote sensing is detecting electromagnetic radiation (EMR) from satellite sensors. This is helpful to analyze spectral response which is EMR emitted from an object in different ways.
The earth’s surface emits and reflects solar radiance during day but only there is emission at night. There are many studies using day and night data to retrieval LST, e.g. NOAA/AVHRR. In the spectral region there are regions which called atmospheric windows (3-4 µm and 8-13 µm), in this region the absorption of atmosphere is minimum and waves can pass with less attenuation.

The first derivative of Planck’s law explained about the sensitivity to changes in LST:

$$\frac{dT}{dB} = \frac{C_1 C_2 \lambda^{-5} e^{C_2/\lambda T}}{\pi T^2 (e^{C_2/\lambda T} - 1)^2}$$  \hspace{1cm} (7)

where, the variables/constants are the same as in equation (2). Figure 4 shows B and dB (λ,T)/dT for a black body at T=300 K. The two curves are discrete by 1.7 µm: near the maxima of B (i.e. λ_m=9.7µm) dB/dT is also close to its maximum ratio.

Relationship Between Radiance and Temperature: The Radiative transfer equation in the infrared region is following assumes:

- The rang of thermodynamic equilibrium in the local atmosphere is almost acceptable up to about 50-70 km.
- Only clear sky and non-smoggy conditions are considered, which means there is not scattering.
- The surface of the Earth’s action is between a Lambertian and a specular reflector.

To retrieval land surface temperature from TIR region for a selected satellite sensor band i based on the radiative transfer equation is;

$$L_{sat} = \int \alpha_2 f_2(\lambda) \sigma(\lambda) B(\lambda, T, \theta, \phi) d\lambda$$

$$\int \frac{\alpha_2}{\rho_{atm}} f_2(\lambda) B(\lambda, T, \theta, \phi) \frac{d\tau}{dp} d\lambda dp$$

$$+ \int \alpha_2 \int_{0}^{2\pi} \int_{0}^{\pi} (1-e^{-\tau}) f_i(\lambda) L^s(\lambda, \theta, \phi)$$

$$\tau(\lambda) \sin 2\theta \partial \phi d\theta d\phi$$  \hspace{1cm} (8)

where, i channel; \( f_i \) response function of normalized channel; \( \theta \) zenith angle; \( \phi \) azimuth angle; \( \lambda \) wavelength, \( \lambda_1, \lambda_2 \) lower and upper limits of spectral range; \( p \) pressure, \( p_{atm} \) pressure at Earth’s surface; \( \tau(\lambda) \) spectral atmospheric transmissivity; \( \varepsilon(\lambda) \) surface spectral emissivity; \( T_s \) surface temperature;

\( L^s(\lambda, \theta, \phi) \) downwelling atmospheric radiance (downwelling irradiance divided by\( \pi \)); \( T_p \) mean temperature of air at pressure level \( p \).

Satellites and LST Sensors: Figure 5 and Table 1 show satellite sensor timetable availability and current LST satellite sensor data information, respectively. As can be seen thermal sensors have problem in both spatial and temporal resolutions in acquisition of LST. Those thermal sensors with high temporal resolution have low spatial resolution (e.g. MODIS, AVHRR, AASTR, SEVIRI and GOES), on the other hand, sensors with high spatial resolution have problem in temporal resolution (e.g. Landsat series, ASTER). These limitations in data acquisition make drawbacks in estimation of LST in both high spatial and temporal resolutions for related studies such as urban heat island (UHI) monitoring. To overcome to this problem, need to create suitable downscaling method with high accuracy.

Atmospheric Correction: The temperature emissivity separation needs the surface thermal infrared radiance for generating the LTS and E. It is require isolating land surface features in the atmospheric correction from of the scattering, atmospheric emission and absorption effects in the earth’s surface. There are two ways in calculation of surface radiance;

- Prepare the air temperature and water vapor of the place in the measuring time, from valid products with enough spatial resolution and near to observing time to prevent interpolation errors.
- In computing the atmospheric parameters by radiative transfer model, the atmospheric profiles are as input which is requires estimating the at-surface radiance water vapor, especially in the areas with
high humidity, which will make errors in atmospheric correction. Water vapor, ozone (9.6 µm) and carbon dioxide (14 µm; see Figure 6) have influence on atmospheric transmittance. The influence of aerosol still there is, however, because of the much larger wavelength it is strongly reduced compared to the solar domain. Thus, for retrieving of surface properties (emissivity and surface temperature), an accurate estimate of the water vapor column is require.

The plan of the radiation components in the thermal region seen in Figure 7: path radiation \((L_p)\), emitted surface radiance \((L_s)\) reflected radiance \((L_r)\). Thermal path radiation happens due to atmospheric emitted radiation. Hemispherical downwelling thermal flux \((F)\) also is atmospheric products. As the emissivity \((\varepsilon)\) is less than 1, the radiation reflected from the ground is \((1 - \varepsilon)\) \(F/\pi\), assuming a blackbody surface, that is, \(\rho = 1 - \varepsilon\).

The at-sensor radiance can be written as;

![Fig. 5: Timetable of satellite sensor data availability.](image)

![Table 1: Current LST capable sensors include satellite information.](image)
Fig. 6: Influence of Water vapor, ozone and carbon dioxide Atmospheric transmittance in the 0.4-2.5 µm and 3-14 µm regions.

Fig. 7: Radiation components in the thermal region.

\[ L = I_p + \tau \varepsilon B(T) \ast \tau (1 - \varepsilon) F/\pi \quad (9) \]

where B is Planck’s blackbody function. The problem with this equation is that it includes two unknowns: the emissivity \( \varepsilon \) and temperature T. For most natural surfaces, the emissivity in the 10–12-µm region ranges between 0.95 and 0.99.

Atmospheric Correction Methods for Retrieval of LST

Single-channel methods apply to retrieve and correct the atmospheric effects of land surface temperature in one infrared window channel. Thus, single-channel algorithm can be used to sensors with one IR band, e.g. Landsat 7/ETM+, Meteosat-MVIRI [27].

The single channel methods need accurately, distribution of atmospheric temperature and water vapor in vertical and horizontal situation. The TIROS operational vertical sounder (TOVS) onboard NOAA, visible and infrared spin-scan radiometer atmospheric sounder (VAS), radiosondes and data acquired from numerical weather prediction models are feasible data sources to atmospheric profiles.

Single-channel correction minimize uncertainty essential to the split-window algorithm, however needs an accurate RTM and described atmospheric profile. But, owing to the size of datasets and time consuming, this way is unfeasible for correcting satellite retrievals and needs to radiative transfer models [28]. The radiative transfer model such as MODTRAN used in single channel method.

In the RTM, surface emissivity variations and the atmospheric effect do not linearized. But, onward computations applying radiative transfer model take a long time, on the other hand, long-term datasets of atmosphere require time consume to atmospheric correction, thus, the faster methods are require, e.g. neural networks (NN).

There are many studies using single-channel methods. Sobrino et al. [29] evaluated among radiative transfer equation applying in-situ data and the single-channel algorithm. Jiménez-Muñoz and Sobrino [30] proposed a single-channel algorithm based on the solving for the Planck radiance. They studied about the error sources that have influence on LST estimation with radiative transfer equation, they found that the errors might come from the sensor’s noise, wavelength uncertainty, band-pass effects, land surface emissivity, aerosols, angular effects, other gaseous absorbers, full-width at half-maximum of the sensor and atmospheric correction. According to their results, the most important errors linked with atmospheric effects, which might present an estimation error from 0.2 K to 0.7 K and an error in LSE up to 0.2 K to 0.4 K.

Ellicott [28] proposed a new parametric model for atmospheric correction of TIR Data to assess the accuracy of a single-channel atmospheric correction which is adjusted to MODIS and obtain the similar accuracy from MODTRAN with minimum computing order, the results showed consistent results for retrieval of correction parameter.
To retrieve LST from only one thermal channel [27] developed a generalized single-channel as follow:

\[ T_s = \gamma K \left[ e^{-\psi_2} (\psi_1 \text{L}_{\text{sensor}} + \psi_2 \text{L}_{\text{sensor}}) + \delta \right] \]  

(10)

With:

\[ T_s = \gamma K \left[ e^{-\psi_2} (\psi_1 \text{L}_{\text{sensor}} + \psi_2 \text{L}_{\text{sensor}}) + \delta \right] \]  

(11)

\[ \gamma = \left( \frac{\text{L}_{\text{sensor}}}{\text{L}_{\text{sensor}} + \lambda^{-1}} \right)^{-1} \]  

(12)

\[ \text{L}_{\text{sensor}}: \text{at-sensor radiance in} \ W \ m^{-2} \ sr^{-1} \ m^{-2}, \ T_{\text{sensor}}: \text{at-sensor brightness temperature in K}, \ \lambda: \text{effective wavelength (11.457} \ \mu m \ \text{for band TM6),} \]

[4]

\[ c_1 = 1.19104*10^8 W \ \mu m^4 \ m^{-2} \ sr^{-1} \]

\[ c_2 = 14387.7 \ \mu m \ K. \]

\\(\psi_1, \psi_2\) and \(\psi_3\): The atmospheric functions, which can be acquired as a function of the total atmospheric water vapor content (w) based on the following equations particularized for TM6 data:

\[ \psi_1^{TM6} = 0.14714w^2 - 0.15583w + 1.1234 \]  

(13)

\[ \psi_2^{TM6} = -1.1836w^2 + 0.37607w - 0.52894 \]  

(14)

\[ \psi_3^{TM6} = -0.04554w^2 + 1.8719w - 0.39071. \]  

(15)

Based on Zhang et al. [31] the generalized single-channel method improved by Jiménez-Muñoz and Sobrino [27] can be used to specified thermal sensors with Full-Width Half-Maximum (FWHM) about 1 \(\mu m\) it helps to find out LST from TM6 data with more accuracy. The most advantage of this algorithm among other single-channel methods is that no need to field radiosondings, on the other hand, with compare with SW, it can be used to various thermal sensors with using same equation and coefficients.

\textbf{Split Window Technique}: The Split-window technique achieved from [32]. That was applied for sea surface temperature (SST) estimation. In the infrared spectral, assuming that the radiation is coming from the atmosphere and the surface.

\[ L(\lambda) = B(\lambda, T_s) = \tau(\lambda) B(\lambda, T_s) \]  

(16)

\[ B(\lambda, T_s) = \frac{1}{\pi (c_1)^2} \int_0^\infty B(\lambda, T) d\tau \]  

(17)

where, \(T_s\) is a mean temperature of the atmosphere.

This method performs atmospheric correction to a largely using a linear combination of radiances from two adjacent infrared bands. It is still being applied to acquire sea surface temperature (SST) with the accuracy near to 0.5 K [5]. After success in SST retrieval results, extensively applied for land surface temperature (LST). In the atmospheric windows area, specially the 10.5-12.5 \(\mu m\) range there are broad bands of many operational satellite sensors, the SWT uses the absorption difference between two channels (i.e. NOAA/AVHRR channels 4 and 5) to minimize the atmospheric influence and calculate surface temperature as a linear combination of two brightness temperatures. For channels 4 and 5 of AVHRR, equations (18 and 19) can be given as:

\[ L(4) = B(4, T_{s4}) = \tau(4) B(4, T_s) \]  

(18)

\[ L(5) = B(5, T_{s5}) = \tau(5) B(5, T_s) \]  

(19)

For the two channels it was assumed that: (1) their contribution functions are similar and therefore \(T_s\) is equivalent; and (2) the difference in transmittance results from different absorption coefficients in the two channels and is mainly due to water vapor and not emissivity differences.

\[ T_s = T_4 + a(T_{s4} - T_s) + b \]  

(20)

where, coefficients \(a\) and \(b\) account for atmospheric conditions (related to spectral radiance and transmission) and surface emissivity respectively.

Barker and Li [33] applied a local split-window technique extracted from SST SWT for LST retrieving, which is one of the successful examples. The SWT has some limits to retrieval temperature over heterogeneous land surface due to the emissivity. Because the emissivities of the land surface covers, are not equal to 1 and depends on the channels. Studies in this area pointed out that if emissivities are given with sufficient accuracy, more accurate LSTs can be derived. Other studies tried to extend that to LST extraction well [34].

The SWT requires the knowledge of the atmospheric temperature and water vapor profiles. Some split-window equations have been developed for the land surface temperature with applying water vapor to improve the accuracy of LST retrieval [16,35-38]. For the reason that, the emissivity of earth’s surface has effects on retrieving LST accuracy; however, in arid and semi-arid areas because of important variations of emissivity according time and location, these algorithms do not work well.

Qin et al. [36] tested 17 published split window algorithms for land surface temperature retrieval from NOAA-AVHRR data they found, the algorithm of Qin et al. [36] is the good option, after that algorithms of Sobrino et al. [39] and França and Cracknell [40] had good
Table 2: Most cited split-window equations in the literature

<table>
<thead>
<tr>
<th>Authors</th>
<th>Split-window equations</th>
<th>Satellite</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>McClain et al., 1985</td>
<td>$T_d = 1.035T_e + 3.046 (T_e - T_s) - 283.93 + 273$</td>
<td>–</td>
<td>K</td>
</tr>
<tr>
<td>Price, 1984</td>
<td>$[T_e + 3.33(T_e - T_s)]^{[0.255T_e]} + 0.75T_s(e_4 - e_5)$</td>
<td>NOAA-7</td>
<td>K</td>
</tr>
<tr>
<td>Becker &amp; Li, 1990a</td>
<td>$1.274 + [3.63 + 2.068(\frac{T_e}{T_s}) + 18.924(\frac{T_e}{T_s})^{2}]T_s + 18.63 - 1.912(\frac{T_e}{T_s}) - 19.406(\frac{T_e}{T_s})^{2}$</td>
<td>NOAA-9</td>
<td>K</td>
</tr>
<tr>
<td>Kerr et al., 1992</td>
<td>$T_v = -2.4 + 3.6T_s - 0.6T_e$</td>
<td>NOAA-11</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>$T_v = 3.1 + 3.17T_e - 2.1T_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulivieri et al., 1994</td>
<td>$T_4 = 1.8(T_4 - T_3) + 48(1 - e) - 75(e_4 - e_5)$</td>
<td>NOAAP-11</td>
<td>K</td>
</tr>
<tr>
<td>Soobrino et al., 1997</td>
<td>$T_4 = 0.83 + T_4 + 1.40(T_4 - T_3) + 0.32(T_4 - T_3)^2 + (57 - 5WV)(1 - e) - 161(30WV)(e_4 - e_5)$</td>
<td>NOAA-11</td>
<td>K</td>
</tr>
</tbody>
</table>

C vegetation cover, $T_v$ vegetation temperature, $T_s$ bare soil temperature.

where $T_v$ and $T_e$ are AVHRR channels 4 and 5, the top-of-atmosphere brightness temperatures of, respectively, and,

$$\Delta e = e_4 - e_5$$

$$e = (e_4 - e_5) / 2$$

The pioneers of SWT who introduced and developed that for LST applications are Becker, Li, Sobrino and Wan. Since 1990 to present a number of LST SWTs have been developed in different forms and applied to generate satellite based LST. However, the essence of the theory is approximately same, that is to make a linear relationship among the LST and the brightness temperatures of two adjacent thermal channels, where the algorithm coefficients depend on the spectral land surface emissivities. LST SW algorithms are keeping the similar form to SST SW algorithm. In following Table (2) some Split-window equations are presented.

The empirical SWT of Vidal [45] and the semi-empirical SWT from Kerr et al. [44] are useful for local LST studies. Sobrino et al. [39] proposed SWT which took both LSE and atmospheric transmittance into account. In addition, many researchers improved the SWT with various coefficients with the atmospheric water vapor content as an important absorbing gas in the split-window bands [35, 46]. These methods have problem in obtaining accurate water vapor every time and hence this error is significant in LST retrieval. Pinheiro et al. [19] adopted the split window method improved by Ulivieri et al. [43], which had good performing in the test by [47] can be written as,

$$\text{LST} = T_e + 1.8(T_e - T_s) + 48(1 - e) - 75\Delta e$$  \hspace{1cm} (21)

Pinheiro et al. [19] developed the equation (21) for column of atmospheric water vapor less than 3.0 g/cm2, for semi-arid portions of continental Africa. Jiménez-Muñoz & Sobrino [37] proposed a complete set of SWTs to retrieve LST from TIR sensors onboard the most common satellite: ERS-ATSR2, NVISAT AATSR, Terra/Aqua-MODIS, NOAA series-AVHRR, METOP-AVHRR3, GOES series-IMAGER and MSG1/MSG2 SEVIRI (Table 3).

There are many sensors appropriate for detecting of land surface temperature, e.g. MODIS, AVHRR, AATSR and ASTER which offer more than one channel in the TIR region suitable for SWT to retrieving LST. But, some sensors like Enhanced Thematic Mapper Plus (ETM+) because of one TIR channel, are not suitable for LST retrieval and cannot use for SWT [48]. Li et al. [38] evaluated the SW and single-channel (SC) algorithms to LST retrieval using high-resolution TIR camera. They applied MODTRAN to make certain about atmospheric coefficients of the generalized SW algorithm and J. Muñoz and Sobrino single-channel algorithm based on TIGR (TOVS Initial Guess Retrieval) database. They consider atmospheric water vapor, LSE and noise of the sensor as a total error which have influence in LST estimation. The results showed that the uncertainties of considered parameters would increase the total errors and the accuracy of the single-channel algorithm and split-window in the low atmospheric water vapor is equal,
Table 3: Split-window coefficients (C0-C3) achieved for the various low-resolution thermal infrared sensors

<table>
<thead>
<tr>
<th>Platform-Sensor</th>
<th>λ0 (μm)</th>
<th>a0 (K)</th>
<th>a1 (K^2)</th>
<th>a2 (K/cm^2⋅g^-1)</th>
<th>a3 (K/cm^2⋅g^-2)</th>
<th>τ</th>
<th>δεke (K)</th>
<th>δew (K)</th>
<th>δε (K)</th>
<th>δε (K)</th>
<th>ε(LST) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-ATSR2</td>
<td>10.94</td>
<td>1.064</td>
<td>0.342</td>
<td>37.1</td>
<td>1,81</td>
<td>-131</td>
<td>15.7</td>
<td>0.970</td>
<td>1.1</td>
<td>0.45</td>
<td>1.2</td>
</tr>
<tr>
<td>ENVISAT-AATSR</td>
<td>10.86</td>
<td>1.04</td>
<td>0.299</td>
<td>39.7</td>
<td>0.97</td>
<td>-124</td>
<td>14.8</td>
<td>0.971</td>
<td>1.1</td>
<td>0.42</td>
<td>1.2</td>
</tr>
<tr>
<td>TERRA-MODIS</td>
<td>11.02</td>
<td>1.016</td>
<td>0.206</td>
<td>41.4</td>
<td>0.04</td>
<td>-201</td>
<td>26.6</td>
<td>0.981</td>
<td>0.9</td>
<td>0.60</td>
<td>1.3</td>
</tr>
<tr>
<td>AQUA-MODIS</td>
<td>11.01</td>
<td>1.021</td>
<td>0.241</td>
<td>41.3</td>
<td>0.14</td>
<td>-193</td>
<td>26.3</td>
<td>0.980</td>
<td>0.9</td>
<td>0.59</td>
<td>1.8</td>
</tr>
<tr>
<td>NOAA07-AVHRR</td>
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<td>0.48</td>
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<td>1.061</td>
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<td>-170</td>
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<td>18.7</td>
<td>0.978</td>
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<td>0.236</td>
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<td>GOES13-IMG</td>
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<td>0.998</td>
<td>0.200</td>
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<td>27.26</td>
<td>-50</td>
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<td>0.769</td>
<td>2.8</td>
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<td>MSG1-SEVIRI</td>
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<td>0.931</td>
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<td>0.979</td>
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<td>1.4</td>
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<td>0.904</td>
<td>0.253</td>
<td>45.3</td>
<td>-0.97</td>
<td>-147</td>
<td>18.3</td>
<td>0.979</td>
<td>0.9</td>
<td>0.47</td>
<td>1.4</td>
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</table>

Table 4: Comparison of total errors on LST.

<table>
<thead>
<tr>
<th>emissivity</th>
<th>Water vapor (g/cm²)</th>
<th>LST algorithm</th>
<th>δε_simulation (K)</th>
<th>δε_nadir (K)</th>
<th>δε_emissivity (K)</th>
<th>δε_vapor (K)</th>
<th>δε_total (K)</th>
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<tbody>
<tr>
<td>w=1.5</td>
<td>0.25</td>
<td>Single channel</td>
<td>0.798</td>
<td>0.539</td>
<td>0.289</td>
<td>0.280</td>
<td>1.044</td>
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<tr>
<td>w=3.0</td>
<td>0.30</td>
<td>Single channel</td>
<td>1.165</td>
<td>0.661</td>
<td>0.345</td>
<td>0.345</td>
<td>1.413</td>
</tr>
<tr>
<td>w=4.5</td>
<td>0.35</td>
<td>Single channel</td>
<td>1.94</td>
<td>0.837</td>
<td>0.289</td>
<td>0.280</td>
<td>2.137</td>
</tr>
<tr>
<td>w=1.5</td>
<td>0.25</td>
<td>Split window</td>
<td>0.199</td>
<td>1.028</td>
<td>0.299</td>
<td>0.299</td>
<td>1.089</td>
</tr>
<tr>
<td>w=3.0</td>
<td>0.30</td>
<td>Split window</td>
<td>1.165</td>
<td>0.661</td>
<td>0.345</td>
<td>0.345</td>
<td>1.413</td>
</tr>
<tr>
<td>w=4.5</td>
<td>0.35</td>
<td>Split window</td>
<td>1.94</td>
<td>0.837</td>
<td>0.289</td>
<td>0.280</td>
<td>2.137</td>
</tr>
</tbody>
</table>

about 1K. On the other hand, in high atmospheric water vapor, the accuracy of the SC increased to approximately 2K and the split-window algorithm was constant. Following table shows a comparison of total error on LST (Table 4).

**Multi-Angle Method:** The assumption that the atmosphere is spatially invariant; the multi-angle method utilizes the discrepancy of absorption when the same object is observed from various viewing angles for a given channel. The measurements can be made from different satellites, e.g. Meteosat and TIROS-N. While the emissivity or temperature of when the emissivity or temperature of elements are apparently different, the element of temperature can be inversed by the multi-angle radiance data [49]. Based on suggested technique about dual-angle by Prata [42], a developed dual-angle procedure proposed by Sobrino et al. [39]:

\[
B(T_x) = B(T_n) \cdot a_0 / a_2 - B(T_f) \cdot a_0 / a_2 \cdot (B(T_{ad}) - B(T_{ad})) \cdot a_0 / a_2 \quad (24)
\]

\(n\), nadir viewing by the satellite sensor; \(f\), forward viewing by the satellite sensor and \(a_0\), \(a_1\), and \(a_2\) are given by:
The transmission of separated radiation is estimated by the transmission of directed radiation for the equal bulk of absorbing matter at $\theta = 53^\circ$; $\tau_5$ is applied to account for and to simplification of reflection contribution. The multi-angle method improves accuracy of the retrieved temperature compared to the employment of the split-window method only, particularly for humid atmospheres. According Dash et al. [23] despite of spatial equality of the atmospheric column, the multi-angle method strongly needs one the measurements for longer atmospheric path; in other ways the method becomes variable, on the other hand the surface emissivity angular changes is also required [50].

CONCLUSION

This review has given a brief review of land surface temperature (LST) theoretical background and three most popular retrieval methods include single-channel, split-window and multi-angle techniques. In retrieval of LST from thermal emission in infrared or microwave wavelength region using remote sensing based data, the most popular technique is SWT, due to the accuracy of estimated LST using two thermal bands is higher than compare to single band. In the LST acquisition techniques, only SWT do not need precise atmospheric temperature/water vapour content. It is worth noting that in the single-channel and multi-angle techniques, retrieving emissivity and LST is related to accurate input atmospheric profiles, that uncertainties in the atmospheric profile will cause errors in result. Considering that, there are too many uncertainties involved, e.g., emissitivity determinations, cloud contamination, view angle effect and so on.

However, there are still some drawbacks in trade-off between spatial and temporal resolutions of thermal satellite data in use of LST satellite products. On the hand, uncertainties in LST estimation make it impossible to obtain precise LST product for future studies.

REFERENCES


