ALGORITHMS FOR ESTIMATING LAND SURFACE TEMPERATURE FROM SATELLITE DATA: A BRIEF REVIEW

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ABSTRACT: One of the major applications of the information produced by radiometers on board satellites in the thermal infrared spectral bands is to obtain knowledge of land surface temperature, T_s. The present article reports on the methods available and the algorithms developed for obtaining T_s from satellite data.

Key words: radiometer, thermal infrared, land surface temperature.

INTRODUCTION

Today there are several satellite platforms (NOAA, LANDSAT, TERRA, etc.) fitted with multi-spectrum sensors containing spectral channels in the thermal infrared band (8-14 μm). A number of algorithms have been developed for estimating T_s from the data they provide. Nevertheless, one of the major problems encountered is the combined action of disturbances caused by atmospheric effects – principally water vapour and to a lesser degree carbon dioxide and aerosols – and the varying emissivity of different soil covers [1-2]

The implementation of the monocanal, biangular and split window methods, which make corrections for atmospheric conditions and emissivity, has led to the development of a number of algorithms for estimating T_s from the information provided by different sensors currently in operation: Advanced Very High Resolution Radiometer, **AVHRR,** on board the NOAA satellite; Advanced Along-Track Scanning Radiometer, **ATSR,** on board the ERS-1 (European Remote-Sensing Satellite-1); Moderate-Resolution Imaging Spectroradiometer, **MODIS,** on board the TERRA satellite; Advanced Spaceborne Thermal Emission and Reflection Radiometer, **ASTER,** on board the TERRA platform; Spinning Enhanced Visible and Infrared Imager, **SEVIRI,** on board the Meteosat 9 satellite; Thematic Mapper, **TM**, on board the LandSat4 and LandSat5 satellites; Enhanced Thematic Mapper Plus, **ETM+**, on board the LandSat7 satellite; Thermal Infrared Sensor, **TIRS**, on board the LandSat8 satellite.

The present article looks at the bases of the methods available and presents the different algorithms designed to obtain T_s from satellite data.

ALGORITHMS FOR ESTIMATING LAND SURFACE TEMPERATURE

The theoretical basis for the development of algorithms for estimating T_s is the equation for radiation transfer in the thermal infrared domain. The radiance measured by the L_λ^{sensor} sensor for a wavelength λ is given by the expression:

$$L_\lambda^{sensor}(\theta) = L_\lambda^{superficie}(\theta)\,\tau_\lambda(\theta) + L_\lambda^{atm\uparrow}(\theta) \quad (1)$$

$L_\lambda^{sensor}(\theta)$ is the radiance recorded by the sensor ($W/m^{-2}sr^{-1}\mu m^{-1}$), θ the angle of observation, τ_λ the atmospheric transmissivity, $L_\lambda^{atm\uparrow}(\theta)$ the ascendant atmospheric radiance ($W/m^{-2}sr^{-1}\mu m^{-1}$), and $L_\lambda^{superficie}(\theta)$ the radiance emitted by the soil surface ($W/m^{-2}sr^{-1}\mu m^{-1}$), given by the equation

$$L_\lambda^{superficie}(\theta) = \varepsilon_\lambda(\theta) B_\lambda(\lambda, T_s) + \left[1 - \varepsilon_\lambda(\theta)\right] L_\lambda^{atm\downarrow}(\theta) \quad (2)$$

$\varepsilon_\lambda(\theta)$ is the emissivity of the soil surface, $L_\lambda^{atm\downarrow}(\theta)$ is the descendant atmospheric radiance ($W/m^{-2}sr^{-1}\mu m^{-1}$), and $B_\lambda(\lambda, T_s)$ the radiance emitted by a black body (ε=1) at temperature T_s ($W/m^{-2}sr^{-1}\mu m^{-1}$), defined by Planck's Law:

$$B_\lambda(\lambda, T_s) = \frac{c_1}{\lambda^5 \left[\exp\left(\frac{c_2}{\lambda\, T_s}\right) - 1\right]} \quad (3)$$

$c_1 = 1.19104 \times 10^8$ ($W\, \mu m^4\, m^{-2}\, sr^{-1}$) y $c_2 = 1.43877 \times 10^4$ ($\mu m\, ^oK$) are numerical constants, which we will call Planck coefficients. Considering that the sensor records the information in a band width, the value of λ can be estimated as an effective wavelength, λ_{eff}, taking into account the response function of the sensor $f(\lambda)$

$$\lambda_{eff} = \frac{\int_0^\infty \lambda\, f(\lambda)}{\int_0^\infty f(\lambda)\, d\lambda}\, d\lambda \quad (4)$$

If $f(\lambda)$ is not available, the central wavelength of the spectral channel can be used.

MONOCANAL METHOD

From equation (1), after clearing the radiance of the black body, $B_\lambda(\lambda, T_s)$, we obtain:

$$B_\lambda(\lambda, T_s) = \frac{L_\lambda^{sensor}(\theta) - L_\lambda^{atm\uparrow}(\theta) - \tau_\lambda(\theta)\left[1 - \varepsilon_\lambda(\theta)\right] L_\lambda^{atm\downarrow}(\theta)}{\tau_\lambda(\theta)\, \varepsilon_\lambda(\theta)} \quad (5)$$

which allows T_s to be estimated by inversion of the Planck function. The disadvantage of this method, known as the monocanal method, is that additional information is required to that supplied by the satellite, namely: emissivity, transmissivity, and ascendant and descendant atmospheric radiance. The emissivity can be obtained by one of the methods described in the literature [3-4], while transmissivity and ascendant and descendant atmospheric radiance are available from atmospheric profiles coinciding with the satellite's pass time and from radiative transfer codes (LOWTRAN, MODTRAN).

An approach which makes atmospheric profiles unnecessary is the Thematic Mapper (TM) sensor, spectral band 6 (10.4-12.5 μm), on board LandSat5 [5].

$$T_s = \frac{\left[a_6(1 - C_6 - D_6) + (b_6(1 - C_6 - D_6) + C_6 + D_6)\,T_6 - D_6 T_a\right]}{C_6} \qquad (6)$$

with

$$C_6 = \varepsilon_6\ \tau_6$$

$$D_6 = (1 - \tau_6)\left[1 + (1 - \varepsilon_6)\,\tau_6\right]$$

(7)

$$a_6 = -67.3555351$$

$$b_6 = 0.458606$$

ε_6 is the surface emissivity, T_6 (^{o} K) is the radiometric temperature provided by the sensor, τ_6 the atmospheric transmissivity, and T_a (^{o} K) represents the mean atmospheric temperature. For the latter variables, the authors propose linear expressions as a function of water vapour, w (gr cm^{-2}), and air temperature, T_o (^{o} K), respectively. The approximations are generated depending on the type of standard atmosphere selected (USA, 1976, Tropical, Summer Mid Latitudes, Winter Mid Latitudes). Thus the parameters required to estimate T_s are reduced to: emissivity, transmittance and mean atmospheric temperature.

Another work proposes a generalised algorithm which can be applied to any thermal sensor with bandwidth around 1 μm [6]. As in the previous case, the algorithm is independent of atmospheric radio probes, and it also does not require the atmospheric temperature to be known.

$$T_s = \gamma\left[\varepsilon_\lambda^{\ -1}(\psi_1 L_\lambda^{sensor}(\theta) + \psi_2) + \psi_3\right] + \delta \quad (8)$$

where

$$\gamma = \left\{\frac{c_2\, L_\lambda^{sensor}}{T_{sensor}^2}\left[\frac{\lambda^4}{c_1} L_\lambda^{sensor} + \lambda^{-1}\right]\right\}^{-1}$$

(9)

$$\delta = -\gamma\ L_\lambda^{sensor} + T_{sensor}$$

L_{λ}^{sensor} and T_{sensor} correspond to the radiance and radiometric temperature recorded by the sensor, □□ is the effective wavelength, ψ_1, ψ_2, ψ_3 are specific atmospheric functions, given by the expressions:

$$\psi_1 = \frac{1}{\tau}$$

$$\psi_2 = -L_{\lambda}^{atm\downarrow} - \frac{L_{\lambda}^{atm\uparrow}}{\tau} \qquad (10)$$

$$\psi_3 = -L_{\lambda}^{atm\downarrow}$$

In view of the complexity of obtaining the transmissivity and the ascendant and descendant atmospheric radiance (τ, $L_{\lambda}^{atm\downarrow}$, $L_{\lambda}^{atm\uparrow}$), and with the object of developing more operational expressions for estimating atmospheric functions, the authors propose expressions for ψ_1, ψ_2, ψ_3 expressed as a function of the atmospheric vapour content, w (gr cm^{-1})

$$\psi_k = \eta_{k\lambda} w^3 + \xi_{k\lambda} w^2 + \chi_{k\lambda} w + \varphi_{k\lambda} \qquad (11)$$

or as a matrix

$$\begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix} = \begin{bmatrix} \eta_{1,\lambda} & \xi_{1,\lambda} & \chi_{1,\lambda} & \varphi_{1,\lambda} \\ \eta_{2,\lambda} & \xi_{2,\lambda} & \chi_{2,\lambda} & \varphi_{2,\lambda} \\ \eta_{3,\lambda} & \xi_{3,\lambda} & \chi_{3,\lambda} & \varphi_{3,\lambda} \end{bmatrix} \begin{bmatrix} w^3 \\ w^2 \\ w \\ 1 \end{bmatrix} \qquad (12)$$

$\eta_{k\lambda}, \xi_{k\lambda}, \chi_{k\lambda}, \varphi_{k\lambda}$ are polynomial functions of the 3rd order in the wavelength:

$$\eta_{k\lambda}, \xi_{k\lambda}, \chi_{k\lambda}, \varphi_{k\lambda} = \sum_{j=0}^{3} a_j^{(k)} \lambda^j \qquad (k = 1,2,3) \ (13)$$

The algorithm was applied and validated using three sensors: AVHRR, band 4 ($\lambda \approx 10.8\ \mu m$); ATRS ($\lambda \approx 11\ \mu m$), band 2; and TM, band 6 ($\lambda \approx 11.5\ \mu m$).

Subsequently the algorithm was treated to generalised and particularised updating for the **TM** thermal sensor, band 6 and the **TIRS** sensor, bands 10 (10.6-11.2 □m) ND 11 (11.50 - 12.50 μm) [7]. In this case the expression for□ is expressed as:

$$\gamma = \frac{T_{sen}^{2}}{a_{\gamma} L_{\lambda}^{2\,sensor} + b_{\gamma} L_{\lambda}^{sensor}} \quad (14)$$

with

$$a_{\gamma} \equiv \frac{c_2 \lambda^4}{c_1}$$

(15)

$$b_{\gamma} \equiv \frac{c_2}{\lambda}$$

c_1 c_2 are the Planck coefficients and λ is the effective wavelength. When the numerical values of a_{γ} y b_{γ} are found, it is shown that $a_{\gamma} << b_{\gamma}$, therefore

$$\gamma \approx \frac{T_{sen}^{2}}{b_{\gamma} L_{\lambda}^{sensor}}$$

(16)

$$\delta = T_{sensor} - \frac{T_{sen}^{2}}{b_{\gamma}}$$

and the atmospheric functions are represented as a function of the water vapour, through a grade 2 polynomial

$$\begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} w^2 \\ w \\ 1 \end{bmatrix} (17)$$

c_{ij} are specific coefficients of the sensor.

Another proposed algorithm, developed for the **TIRS** sensor [8] in spectral band 10, corresponds to the expression:

$$T_s = \frac{\left[a_{10}(1 - C_{10} - D_{10}) + (b_{10}(1 - C_{10} - D_{10}) + C_{10} + D_{10})\,T_{10} - D_{10}T_a\right]}{C_{10}} \qquad (18)$$

T_a mean atmospheric temperature; T_{10} radiometric temperature, band 10; a_{10}, b_{10} are coefficients whose values depend on the temperature range; C_{10} and D_{10} are parameters given by the expressions

$$C_{10} = \varepsilon_{10}\,\tau_{10}$$

(19)

$$D_{10} = (1 - \tau_{10})\left[1 + (1 - \varepsilon_{10})\,\tau_{10}\right]$$

C_{10} and D_{10} correspond to the transmittance and surface emissivity of the soil, band 10, LandSat8.

BIANGULAR METHOD

A variant of the monocanal method is used for satellites carrying sensors working in biangular mode, for example the ERS-1 (European Remote-Sensing Satellite-1) which carries the Along-Track Scanning Radiometer, **ATSR**. Compared with other spectro-radiometers, this sensor uses a sweeping method which consists in observing the same point on the earth's surface from two angles with a two-minute interval, i.e. nadir $\approx 0^0$ and forward $\approx 53^0$.

A review of the literature found few works devoted to estimating T_s from **ATSR** data [9-11]. The algorithms found obey a biangular monocanal equation which relates the real soil surface temperature with radiometric temperatures measured from space using two angles of observation.

SPLIT-WINDOW METHOD

This method combines the data obtained simultaneously by two channels in the same atmospheric transmission window. Using the AVHRR sensor, the classic representation of a Split Window algorithm is:

$$T_s = T_4 + A\,(T_4 - T_5) + B \qquad (20)$$

T_4, T_5 correspond to radiometric temperatures in spectral bands 4 and 5; A is a coefficient which depends on the spectral channels used; B is a term to correct the effect of surface emissivity and the absorption-emission of other atmospheric gases than water vapour, mainly carbon dioxide [12-14].

Another representation assumes that coefficient A is written as a linear function of T_4-T_5, and term B as an explicit function of the water vapour content and the emissivity. This is the case with the MODIS sensor, where T_s is found by the expression

$$T_s = T_{31} + a_1 + a_2(T_{31} - T_{32}) + a_3(T_{31} - T_{32})^2 + (a_4 + a_5W)(1-\varepsilon) + (a_6 + a_7W)\Delta\varepsilon \quad (21)$$

T_{31}, T_{32} correspond to the radiometric temperatures in spectral bands 31 and 32; $\varepsilon = (\varepsilon_{31} + \varepsilon_{32})/2$ and $\Delta\varepsilon = (\varepsilon_{31} - \varepsilon_{32})$ are the mean emissivity and the spectral variation of the emissivity in bands 31 (10.7-11.2 μm) and 32 (11.7-12.2 m); W is the water vapour content (gr cm^{-2}); a_1,.. a_7 are constant coefficients [15].

Two new algorithms, the implementation of which is more complex, have recently been developed for the **TIRS** sensor in its spectral bands 10 (10.6-11.2 μm) and 11 (11.5-12.5 μm) [16-17]. The first of these algorithms is:

$$T_s = T_{10} + B_1\,(T_{10'} - T_{11}) + B_0 \quad (22)$$

where

$$B_0 = \frac{C_{11}(1 - A_{10} - C_{10})\,L_{10} - C_{10}(1 - A_{11} - C_{11})\,L_{11}}{C_{11}\,A_{10} - C_{10}\,A_{11}}$$

(23)

$$B_1 = \frac{C_{10}}{C_{11}\,A_{10} - C_{10}\,A_{11}}$$

with

$$A_{10} = \varepsilon_{10}\,\tau_{10}$$

$$A_{11} = \varepsilon_{11}\,\tau_{11} \quad (24)$$

$$C_{10} = (1 - \tau_{10})\,(1 + (1 - \varepsilon_{10})\,\tau_{10})$$

$$C_{11} = (1 - \tau_{11})\,(1 + (1 - \varepsilon_{11})\,\tau_{11})$$

T_{10}, T_{11}; ε_{10}, ε_{11}; τ_{10}, τ_{11} are the radiometric temperatures, emissivities and transmissivities in spectral bands 10 and 11; L10, L11 are parameters with temperature dimensions obtained from a linear equation of the type

$$L_i = a_i + b_i\,T_i \quad (i = 10, 11) \quad (25)$$

coefficients a_i, b_i assume values depending on the temperature range.

The structure of the second algorithm is

$$T_s = b_0 + (b_1 + b_2 \frac{1-\varepsilon}{\varepsilon} + b_3 \frac{\Delta\varepsilon}{\varepsilon^2}) \frac{T_{10} + T_{11}}{2} + (b_4 + b_5 \frac{1-\varepsilon}{\varepsilon} + b_6 \frac{\Delta\varepsilon}{\varepsilon^2}) \frac{T_{10} - T_{11}}{2} + b_7 (T_{10} - T_{11})^2 \quad (26)$$

T10, T11 are the radiometric temperatures in spectral bands 10 and 11; □□□□□□ correspond to the mean emissivity and the spectral variation of the emissivity; b0,..b7 are coefficients whose values have been determined for different atmospheric conditions.

CONCLUSIONS

This review has examined different algorithms developed for estimating T_s based on monocanal, biangular and bicanal methods. While algorithms based on monocanal and biangular methods require information from radio probes, which is sometimes difficult to obtain, the algorithms which use the split window method need other parameters (emissivity, atmospheric transmissivity, mean atmospheric temperature) which can be obtained in various ways.

The choice of the algorithm used is strictly related to the satellite's operating conditions, the sensor's radiometric and spatial properties and the periods between passes of the satellite over a particular spot. As long as satellite platforms exist which can provide daily images, the assumed cost is associated with the pixel spatial resolution (for example the pixel spatial resolution of the AVHRR sensor is 1 km^2). There are other platforms where the pass frequency is of several days, but which have a very good pixel spatial resolution (for example the TIRS sensor which provides information every 16 days with a spatial resolution of 100 m).

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