Derivation of split-window algorithm to retrieve land surface temperature from MSG-1 thermal infrared data

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Abstract

One of the most important parameters in the exchange of energy between the ground and the atmosphere is the land surface temperature (LST). In this work, a split-window algorithm for deriving LST from the first Meteosat Second Generation satellite (MSG-1) data using the two thermal infrared channels IR10.8 and IR12.0 is proposed and validated with in-situ measured temperatures. This algorithm is obtained starting from the radiance transfer equation and requires the knowledge of total atmospheric water vapor content (TAWV) and the surface emissivity ($\varepsilon_{10.8}$ and $\varepsilon_{12}$). First, we have simplified the Planck function to retrieve the radiance at MSG-1 from the temperature. Then, the Roberts model was used to create a relationship between atmospheric transmittance and TAWV. Next, sensitivity analysis of the algorithm indicates that the possible error of viewing angle has relatively insignificant impact on the probable LST estimation error, which is sensible to the possible error of ground emissivity and TAWV. Finally, two methods have been used to validate the proposed algorithm. On the one hand, the results show a root mean square error (RMSE) equals 0.79 K and an average accuracy equals 0.45 K for the comparison with another algorithm. On the other hand, the results show a RMSE equals 2.75 K and an average accuracy equals 1.96 K for the comparison with in-situ measurements. We conclude that the proposed algorithm is able to provide an accurate LST.

Keywords: Land surface temperature, split-window algorithm, MSG-1, Roberts model, total atmospheric water vapor content.

Introduction

Land surface temperature (LST) is an important factor controlling most physical, chemical and biological processes of the earth [Maik et al., 2004]. For large areas, LST can only be derived from surface-leaving radiation measured by satellite sensor [Dash et al., 2002]. The thermal infrared spectral region (8-13 µm) is particularly interesting for earth observation; it is one of the most transparent regions for the atmosphere, and it contains the maximum thermal emission at terrestrial temperatures [Price, 1983; Becker and Li, 1990]. The thermal infrared radiation emitted from Earth surfaces will be perturbed by the atmosphere...
before reaching a sensor [French et al., 2003; Tarantino, 2012]; where the water vapor is the principal factor for atmospheric effects which are very variable as a consequence of the wide seasonal and latitudinal variability of atmospheric moisture [Sobrino et al., 1991]. The three major effects of the atmosphere are absorption, upward atmospheric emission, and the downward atmospheric irradiance reflected from the surface [Dash et al., 2007]. In the thermal infrared region, we can neglect the aerosol absorption and scattering, although we can neglect the absorption and emission by CO$_2$, O$_3$, etc. [Price, 1983]. Atmospheric correction is, therefore, necessary for the retrieval of LST.

Various methods have been proposed for estimating sea surface temperature (SST) and LST from satellite data. The first one proposed by Price [1983] in which he uses one single channel of the infrared radiometer and it is based on the linearization of the radiance transfer equation. This methodology requires a precise description of the atmospheric structure which can be provided by climatological data or better by radiosonde measurements [Ottlé et al., 1992]. The second method for estimating the surface temperature is called the split-window. This method was first suggested by Anding and Kauth [1970] and developed by Prabhakara et al. [1974], Deschamps and Phulpin [1980], Price [1984], François and Ottlé [1996], Mao et al. [2005], and Trigo et al. [2008]; they showed that the surface temperature can be estimated by the use of two infrared radiances measured in two channels in the thermal infrared window.

Many papers have been published to retrieve LST from the first Meteosat Second Generation satellite (MSG-1) data. For instance, Sobrino and Romaguera [2004] retrieved LST using the split-window method proposed by Sobrino et al. [1996] from MSG-1 data. Jiang and Li [2008] derived LST from MSG-1 data using the generalized split window (GSW) method proposed by Becker and Li [1990] and improved by Wan and Doizer [1996]. Jiménez-Munoz and Sobrino [2008] also proposed a split-window algorithm can be used to estimate LST from MSG-1.

In this paper, we present a novel contribution for the split-window technique in which we provide another split-window algorithm with less parameters and high accuracy, it can be used for retrieving LST from MSG-1 data using the two thermal infrared channels IR10.8 and IR12. The main advantages of this algorithm are the following: It is a physics-based algorithm, since it is obtained from the radiance transfer equation applied to two different bands; it takes into account both emissivity and water vapor effects; it includes both LST and SST cases; and it is totally operational. To derive and validate this algorithm, we have first simplified the Planck function to retrieve the radiance at MSG-1 from the temperature. Then, the ‘Roberts’ model was used to create a relationship between atmospheric transmittance and total atmospheric water vapor content (TAWV). Therefore, we used the radiance transfer equation to extract the LST as a function of TAWV and surface emissivity ($\varepsilon_{10.8}$ and $\varepsilon_{12}$) and viewing angle ($\theta$). Next, two methods have been used to validate the proposed algorithm. Finally, we try to present an example of its application to the Algiers-Mediterranean sea border region for the examination of the surface temperature difference on both sides of the border region.

**Data**

**MSG-1 data**

MSG-1 is a new generation of the geostationary satellite developed by European Space Agency (ESA) and EUMETSAT [Jiang, 2007]. The MSG-1 was launched on August 29,
2002 by the Ariane 5 rocket. MSG-1 has a cylindrical body, with a diameter of 3.2 m and a height of 2.4 m, rotating along its longitudinal axis which is aligned with the Earth’s rotation axis, at 100 rpm speed. This stabilizes the satellite as well as allows a progressive scanning of the Earth [Julien, 2008]. Two sensors are placed on this satellite; the Geostationary Earth Radiation Budget (GERB), and the Spinning Enhanced Visible and Infrared Imager (SEVIRI). The SEVIRI is the main payload on board MSG-1 [Sobrino and Romaguera, 2004]. SEVIRI has 3 channels dedicated to visible and near-infrared, centered at 0.6, 0.8 and 1.6 μm, 8 channels for the infrared, centered at 3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0 and 13.4 μm, and finally a broad band (0.5 to 0.9 μm) in the visible, called High-Resolution Visible (HRV) channel. These channels are respectively named VIS0.6, VIS0.8, IR1.6, IR3.9, WV6.2, WV7.3, IR8.7, IR9.7, IR10.8, IR12.0, IR13.4, and HRV [Julien, 2008]. In this work, we use the radiance measured by the channels IR10.8 and IR12.0 μm. The thermal channel radiance may be converted into brightness temperature [Clerbaux, 2006] by using the following relationship:

\[
T_i = \frac{1}{A} \left[ \frac{C_2 \nu_c}{\log \left( \frac{C_1 \nu_c^3}{L_{sat}} + 1 \right)} - B \right]
\]  

where \(T_i\) is the brightness temperature in K, \(L_{sat}\) is the radiance at MSG-1 in \(mWm^{-2}sr^{-1}(cm^{-1})^{-4}\), \(\nu_c\) is the wave number in \(cm^{-1}\), \(A\) and \(B\) are constants (Tab. 1). \(C_1\) and \(C_2\) are the radiation constants, their values are:

\[
C_1 = 1.19104 \times 10^{-5} mWm^{-2}sr^{-1}(cm^{-1})^{-4}, \quad \text{and} \quad C_2 = 1.43877 K(cm^{-1})^{-1}
\]

| Channel | \(\nu_c\) (cm\(^{-1}\)) | A     | B     |
|---------|-----------------|-------|-------|
| IR10.8  | 930.659         | 0.9983| 0.627 |
| IR12.0  | 839.661         | 0.9988| 0.397 |

**In-situ data**

In the framework of the African Monsoon Multidisciplinary Analysis (AMMA) Enhanced Observing Period [Redelsperger et al., 2006] West Africa has been extensively instrumented. In particular, the Kobou site located in Mali at 14.7284°N, 1.5021°W includes a soil temperature measurement that will be used for validation of our proposed algorithm. Some details about the sensor used for measuring the in-situ LST data:

- The distance between the ground and the sensor: 3m;
- Manufacturer of the sensor: APOGEE;
- Model of the sensor: IRTS-P (Precision Infrared Temperature Sensor).
The Kobou site includes also a relative humidity and air temperature measurements that will be used to calculate the TAWV using the formula of Reitan [1963]:

\[ W = 0.1 \exp\left[0.052 \left(T_d - 273.15\right) + 2.37\right] \quad [2a] \]

where \( W \) is the TAWV \((\text{g/cm}^2)\) and \( T_d \) is the dew point temperature \((\text{K})\) which is calculated from air temperature and relative humidity as follow:

\[ T_d = \frac{8}{100} \left[ H \left(112 + 0.9\left(T_0 - 273.15\right)\right) + 0.1\left(T_0 - 273.15\right) + 161.15 \right] \quad [2b] \]

where \( H \) is the relative humidity \((\%)\) and \( T_0 \) is the air temperature \((\text{K})\).

**Sobrino and Romaguera’s algorithm data**

Sobrino and Romaguera [2004] have developed a split-window algorithm in order to retrieve LST from the two channels IR10.8 and IR12 of MSG-1, in which the LST is given by the following Equation:

\[
T_s = T_{IR10.8} + \left[3.17 - 0.64 \cos \theta \right] \left(T_{IR10.8} - T_{IR12}\right) + \left[-0.05 + \frac{0.157}{\cos \theta} \right] \left(T_{IR10.8} - T_{IR12}\right)^2 \\
+ \left[65 - \frac{4}{\cos^2 \theta}\right] \left(1 - \varepsilon\right) + \left[-11.8 + \frac{5.1}{\cos \theta}\right] W \left(1 - \varepsilon\right) + \left[-180 + \frac{24}{\cos \theta}\right] \Delta \varepsilon \\
+ \left[-4 + 34 \cos \theta\right] W \Delta \varepsilon - 0.6 \quad [3]
\]

where:

\[ \Delta \varepsilon = \left(\varepsilon_{10.8} - \varepsilon_{12}\right) \]

and

\[ \varepsilon = \frac{\varepsilon_{10.8} + \varepsilon_{12}}{2} \]

The LST data retrieved by the Sobrino and Romaguera’s algorithm will be used for validation of our proposed algorithm. This algorithm has been selected for validation because it also uses the MSG-1 data for estimating LST and because it is shown that the LST can be obtained from MSG-1 data with accuracy lower than 1.5 K for the most of the situations between nadir and 50° of viewing angle [Sobrino and Romaguera, 2004].

**Role of the atmosphere**

In the thermal infrared window, water vapor is mainly responsible for atmospheric effects. The thermal infrared radiation emitted from Earth surfaces will be perturbed by the atmosphere before reaching a sensor. Indeed, for a clear atmosphere in local thermodynamic equilibrium, the radiance measured by a thermal infrared radiometer can be written as follow [Ottlé and Stoll, 1993]:

\[
L_{sat} = B(T_s) = \tau \left[ \varepsilon B(T_s) + \left(1 - \varepsilon\right) L_{atm}^\uparrow \right] + L_{atm}^\uparrow \quad [4]
\]
where $T_i$ is the brightness temperature, $\tau$ is the atmospheric transmission, $\epsilon$ is the surface emissivity, $B(T_s)$ is the Planck function at the surface temperature $T_s$, $L_{atm}^{up}$ and $L_{atm}^{down}$ are respectively the upward atmospheric radiance and downward atmospheric radiance. For an atmospheric profile-type tropical, we have shown in Figure 1 the variation of the spectral response of eight channels of MSG-1 and the brightness temperature at MSG-1 for a surface temperature $T_s=310K$ and a surface emissivity equals 0.98 as a function of wave number (calculation made with the code 4A/OP). We note that both thermal infrared channels IR10.8 and IR12.0 of MSG-1 are in atmospheric window between 760 and 1000 cm$^{-1}$ corresponding brightness temperatures warm.

\[ \tau = \exp\left(-\frac{\sigma \lambda z}{\cos \theta}\right) \]  

\[ [5] \]
where $\theta$ is sensor view angle, $z$ is nadir view path length and $\sigma_\lambda$ is the water vapor continuum extinction coefficient ($m^{-1}$), the value of $\sigma_\lambda$ given by Roberts et al. [1976] is used:

$$
\sigma_\lambda = \rho \left[ e + 0.002(P - e) \right] \left[ 0.004124 + 5.509 \exp \left( -\frac{78.7}{\lambda} \right) \right] \exp \left[ 1800 \left( \frac{1}{T - \frac{1}{296}} \right) \right] \quad [6]
$$

where $\rho$ is water vapor density ($Kg \ m^{-3}$), $e$ is the water vapor pressure component ($kPa$), $P$ is the atmospheric pressure ($kPa$), $\lambda$ is the wavelength ($\mu m$) and $T$ is the atmospheric temperature ($K$).

To calculate the total monochromatic transmittance of the atmosphere we multiplied the different transmittances atmospheric layers between them, and to calculate the total transmittance in a channel $i$ we use the following formula:

$$
\tau_i = \frac{\int f_i(\lambda) \tau_\lambda d\lambda}{\int f_i(\lambda) d\lambda} \quad [7]
$$

where $f_i(\lambda)$ is the spectral response of the radiometer in channel $i$.

**Atmospheric radiance**

The upward atmospheric radiance and downward atmospheric radiance are defined respectively by:

$$
L^\uparrow_{atm} = \int_0^z B(T_z) \frac{\partial \tau(z, Z)}{\partial z} dz \quad [8]
$$

$$
L^\downarrow_{atm} = 2 \int_0^{\pi/2} \int_0^{\theta'} B(T_z) \frac{\partial \tau'(\theta', z, 0)}{\partial z} \cos \theta' \sin \theta' dz d\theta' \quad [9]
$$

where $T_z$ is the temperature of the atmosphere at the altitude $z$, $Z$ is the altitude of the satellite, $\tau(z, Z)$ is the atmospheric transmission ascending, $\theta'$ is the angle between the direction of the downward atmospheric radiance and the vertical direction and $\tau'(\theta', z, 0)$ is the downward atmospheric transmission between the altitude $z$ and the surface.

According to reference [Qin et al., 2001], we can rewrite the upward atmospheric radiance in the following form:

$$
L^\uparrow_{atm} = (1 - \tau) B(T_a) \quad [10]
$$

where $T_a$ is the effective mean atmospheric temperature and $B(T_a)$ is the effective atmospheric radiance.
The radiance $L_{\text{atm}}^\downarrow$, distributed in the hemisphere above the surface, is reflected by the surface that is not a black body. According to the same reference, we can rewrite the downward atmospheric radiance to a good approximation as follow:

$$L_{\text{atm}}^\downarrow = 2\int_0^{\pi/2} (1 - \tau) B(T_a) \cos \theta' \sin \theta' d\theta' \quad [12]$$

Integrating this Equation gives:

$$L_{\text{atm}}^\downarrow = (1 - \tau) B(T_a) \quad [13]$$

Note: In all the following, ‘Roberts’ model will refer to the calculations of the atmospheric transmittance and radiances that were made using the Equation [6].

**The simplification of Planck function and atmospheric transmittance**

**The simplification of Planck function**

To find the relationship between temperature $T$ and the Planck function normalized $B_i(T)$ in both bandwidth IR10.8 and IR12 of MSG-1 we have used the method of least squares. The Planck function normalized is calculated as $B_i(T) = \left( \int f_i(\lambda) B_i(T) \, d\lambda \right) / \left( \int f_i(\lambda) \, d\lambda \right)$ where $f_i(\lambda)$ is the spectral response of the radiometer in channel $i$. We have shown in Figure 2 and 3 the variation of $\ln B_i(T)$ as a function of $1/T$. A number of situations were designed for the calculation. We compute the radiance by Planck function between 260 and 330K in temperature for the effect wavelength of MSG-1 channels IR10.8 and IR12. The results show that $\ln B_i(T)$ depends linearly with $1/T$ (i.e., $\ln B_i(T) = a_i + b_i/T$) with a correlation coefficient equals $-1$. So, the relationship between temperature and the Planck function normalized for channels IR10.8 and IR12.0 of MSG-1 can be reformulated as follow:

$$B_{10.8}(T) = \exp \left( a_1 + \frac{b_1}{T} \right) \quad [14]$$

$$B_{12}(T) = \exp \left( a_2 + \frac{b_2}{T} \right) \quad [15]$$

where:

$a_1 = 7.5531$, $b_1 = -1578.60109$ K;

$a_2 = 6.78886$, $b_2 = -1354.87783$ K.
Figure 2 - Variation of $\ln(B_{10.8}(T))$ as a function of $(1/T)$ for channel IR10.8.

Figure 3 - Variation of $\ln(B_{12}(T))$ as a function of $(1/T)$ for channel IR12.
The simplification of atmospheric transmittance

To determine the relationship between the total atmospheric transmittance in channel $i$ ($\tau_i$) and the TAWV we use the method of least squares. A number of situations were designed for the calculation; we used six atmospheric profiles (Tropical, Mid-Latitude Summer, Mid-Latitude Winter, Sub-Arctic Summer, Sub-Arctic Winter and 1976 U.S. Standard) which are also used by Modtran3.5, and we used six viewing angles ($\theta = 0, 10, 20, 30, 40$ and $50^\circ$). The results are shown in Figure 4 and 5. The method of least squares indicates that for channel IR10.8 of MSG-1 we have

$$1 - \tau_{10.8} = -0.00505W^3 + 0.04029W^2 + 0.02469W \cos \theta$$

and for channel IR12 of MSG-1 we have

$$1 - \tau_{12} = -0.00817W^3 + 0.05549W^2 + 0.04325W \cos \theta$$

So, the relationship between the TAWV and the total atmospheric transmittance for channels IR10.8 and IR12 can be reformulated as follow:

$$\tau_{10.8} = 1 - \frac{-0.00505W^3 + 0.04029W^2 + 0.02469W \cos \theta}{[16]}$$

$$\tau_{12} = 1 - \frac{-0.00817W^3 + 0.05549W^2 + 0.04325W \cos \theta}{[17]}$$

where $W$ is the TAWV ($g/cm^2$).

Figure 4 - Variation of the atmospheric transmittance of channel IR10.8 as a function of the TAWV for six atmospheric profiles and for six viewing angles $0, 10, 20, 30, 40$ and $50^\circ$, we have also added the points ($W = 0, \tau = 1$), calculation made with the 'Roberts' model.
Proposed split-window algorithm

The atmosphere absorbs and diffuses the radiation emitted by the soil and by the atmosphere itself. Thus, correction is necessary for retrieving true LST. The split-window algorithm, as presented in this paper, uses the two thermal infrared channels IR10.8 and IR12. The basis of this algorithm is that the radiance attenuation for atmospheric absorption is proportional to the radiance difference of simultaneous measurements at the two channels, each subject to different amounts of atmospheric absorption. To reach this algorithm we must go through the following steps:

First, substituting formulas $L_{\text{at}}^{\uparrow}$ and $L_{\text{at}}^{\downarrow}$ in Equation [4], therefore we find the following Equation [Qin et al., 2001]:

$$B(T_{s}) = \tau \epsilon B(T_{s}) + (1 - \tau)(1 + \tau(1 - \epsilon))B(T_{a})$$  \[18\]

To extract $T_{s}$ from Equation [18], we need to linearize Planck’s radiance function. Because the relationship between the Planck’s radiance and temperature is very close to linearity in a narrow temperature range (say, <15°C) for a specific wavelength [Qin et al., 2001], using a first order Taylor expansion of the Planck function in the vicinity of the brightness temperature, we have:
\[
B(T) = B(T_i) + (T - T_i) \left( \frac{\partial B(T)}{\partial T} \right)_{T_i} = \left[ T - T_i + L(T_i) \right] \left( \frac{\partial B(T)}{\partial T} \right)_{T_i} \tag{19}
\]

where \( L(T) \) is defined by:

\[
L(T_i) = \frac{B(T_i)}{\left( \frac{\partial B}{\partial T} \right)_{T_i}} \tag{20}
\]

By applying the Relation [19] on the surface temperature, effective mean atmospheric temperature and brightness temperature, we find:

\[
B(T_s) = \left[ T_s - T_i + L(T_i) \right] \left( \frac{\partial B(T)}{\partial T} \right)_{T_i} \tag{21}
\]

\[
B(T_a) = \left[ T_a - T_i + L(T_i) \right] \left( \frac{\partial B(T)}{\partial T} \right)_{T_i} \tag{22}
\]

\[
B(T_i) = \left[ T_i - T_i + L(T_i) \right] \left( \frac{\partial B(T)}{\partial T} \right)_{T_i} = L(T_i) \left( \frac{\partial B(T)}{\partial T} \right)_{T_i} \tag{23}
\]

By replacing the Equations [21], [22] and [23] in Equation [18] we can come to the following Equation:

\[
L(T_i) = \varepsilon\tau \left[ T_s - T_i + L(T_i) \right] + (1 - \tau) [1 + \tau (1 - \varepsilon)] \left[ T_a - T_i + L(T_i) \right] \tag{24}
\]

Substituting formulas [14] and [15] in Equation [20] we find:

\[
L(T_{10.8}) = \frac{-T_{10.8}^2}{b_1} \tag{25}
\]

\[
L(T_{12}) = \frac{-T_{12}^2}{b_2} \tag{26}
\]

where \( T_{10.8} \) and \( T_{12} \) are respectively the brightness temperature of channels IR10.8 and IR12.
Substituting these Equations into Equation [24] we obtain a system of two Equations, the solution of this system gives the formula of LST as follow:

\[ T_s = \mu_1T_{10.8}^2 + \mu_2T_{12}^2 + \mu_3T_{10.8} + \mu_4T_{12} \quad [27] \]

where:

\[ \mu_1 = -\frac{\alpha_1}{(1 - \beta_2 - \frac{1}{1 - \beta_1})(1 - \beta)} \]

\[ \mu_2 = \frac{\alpha_2}{(1 - \beta_2 - \frac{1}{1 - \beta_1})(1 - \beta)} \]

\[ \mu_3 = -\frac{\beta_1}{(1 - \beta_2 - \frac{1}{1 - \beta_1})(1 - \beta)} \]

\[ \mu_4 = \frac{\beta_2}{(1 - \beta_2 - \frac{1}{1 - \beta_1})(1 - \beta)} \]

and the coefficients \((\alpha_1, \alpha_2, \beta_1, \text{ and } \beta_2)\) have been written depending on the TAWV and the viewing angle instead of the atmospheric transmittance as follow:

\[ \alpha_1 = \frac{(e_{10.8} - 1)}{e_{10.8}b_1}\left(1 - \frac{-0.00505W^3 + 0.04029W^2 + 0.02469W}{\cos(\theta)}\right) \]

\[ \alpha_2 = \frac{(e_{12} - 1)}{e_{12}b_2}\left(1 - \frac{-0.00817W^3 + 0.05549W^2 + 0.04325W}{\cos(\theta)}\right) \]

\[ \beta_1 = \frac{1 + (e_{10.8} - 1)\left(1 - \frac{-0.00505W^3 + 0.04029W^2 + 0.02469W}{\cos(\theta)}\right)^2}{e_{10.8}\left(1 - \frac{-0.00505W^3 + 0.04029W^2 + 0.02469W}{\cos(\theta)}\right)} \]

\[ \beta_2 = \frac{1 + (e_{12} - 1)\left(1 - \frac{-0.00817W^3 + 0.05549W^2 + 0.04325W}{\cos(\theta)}\right)^2}{e_{12}\left(1 - \frac{-0.00817W^3 + 0.05549W^2 + 0.04325W}{\cos(\theta)}\right)} \]

The values of the coefficients b1 and b2 have been given in the Equations [14] and [15].
Results and Discussion

**Sensitivity analysis of the proposed split-window algorithm**

To analyze the sensitivity of our proposed algorithm, we calculated the probable LST estimation error ($\delta T_s$) which is given as follow:

$$\delta T_s = \left| T_s (x + \delta x) - T_s (x) \right|$$  \[28\]

where $x$ is a variable that can be the surface emissivity $\varepsilon$, the total atmospheric water vapor content $W$ or the viewing angle $\theta$, $\delta x$, is the possible error on the variable $x$.

Sensitivity analysis needs a comprehensive simulated data set and it is performed under several conditions. First of all, the emissivity of natural surfaces generally varies in the range 0.95-0.98 for thermal infrared wavelength [Price, 1984; Qin et al., 2001]. So, we consider and we choose a value of surface emissivity of the channels IR10.8 and IR12 in this range for the sensitivity analysis. Secondly, a clear sky is very important and we consider a TAWV of 2 g/cm$^2$ for the analysis.

For brightness temperature of channels IR10.8 and IR12, we assume that $T_{10.8}$ is greater than $T_{12}$ and that their difference is $T_{10.8} - T_{12} = 1K$, this assumption is rational for most cases. Then we have to assume a temperature range for the analysis. Considered the possible land surface temperature change of the Earth, 270K-340K is selected as the range of brightness temperature $T_{10.8}$ change. The result computed by the algorithm indicates that the $\delta T_s$ is almost independent with temperature change. For a possible error on the TAWV ($\delta W$) equals 0.5 g/cm$^2$ the $\delta T_s$ only change 0.021K, within the temperature range 270K-340K, from 0.149K at 340K to 0.17K at 270K. This small change is negligible in practice. Thus, as an example in the following analysis we consider that $T_{10.8} = 286K$ and $T_{12} = 285K$.

**Sensitivity analysis to surface emissivity**

The sensitivity analysis of the proposed split-window algorithm to the surface emissivity was made for a value of $W$ equals 2 g/cm$^2$ and for a viewing angle $\theta = 10^\circ$. Also we consider a surface emissivity of channel IR12 ($\varepsilon_{12}$) equals 0.98.

We have shown in Figure 6 the evolution of $\delta T_s$ as a function of the surface emissivity of channel IR10.8 ($\varepsilon_{10.8}$) for different values of the possible error on the surface emissivity ($\delta \varepsilon_{10.8}$). Clearly we note that $\delta T_s$ decreasingly varies with $\varepsilon_{10.8}$, it also decreases rapidly with strong variations $\varepsilon_{10.8}$. The results show that a variation of $\varepsilon_{10.8}$ equals 0.001 causes a variation of $\delta T_s$ from 0.12K to 0.31K. Furthermore, a variation of $\varepsilon_{10.8}$ equals 0.006 causes a variation of $\delta T_s$ from 0.73K to 1.79K. So the algorithm is very sensitive and requires a true value of the surface emissivity.

We have shown in Figure 7 the same results obtained previously but here as a function of $T_s$. These results show that $\delta T_s$ varies increasingly with $T_s$; it also increases rapidly with large variations of $\varepsilon_{10.8}$.

We have shown in Figure 8 variation of the $\delta T_s$ as a function of the possible error in the surface emissivity of channel IR10.8 and IR12 and two channels at once. This study was made with a surface emissivity $\varepsilon_{10.8} = \varepsilon_{12} = 0.98$. The results show that $\delta T_s$ varies increasingly with the possible error on the surface emissivity in which we found that the variation of $\delta T_s$ for channel IR10.8 is larger comparing to the channel IR12 and both channels at once.
A variation on the surface emissivity equals 0.001 for the channel IR10.8 and the channel IR12 and the two channels at once give an error respectively $\delta T_s$ equals $0.18K$, $0.08K$ and $0.04K$. In addition, a variation on the surface emissivity equals 0.012 for the channel IR10.8 and the channel IR12 and the two channels at once give an error respectively $\delta T_s$ equals $2K$, $0.94K$ and $0.53K$.

Figure 6 - Evolution of the probable LST estimation error as a function of the surface emissivity of channel IR10.8 for different values of the possible surface emissivity error of channel IR10.8.

Figure 7 - Evolution of the probable LST estimation error as a function of the LST for different values of the possible surface emissivity error of channel IR10.8.
Sensitivity analysis to total atmospheric water vapor content

The TAWV is very variable in time and in space. To study the sensitivity of the proposed split-window algorithm we consider that the viewing angle $\theta = 10^\circ$, and the surface emissivity $\varepsilon_{10.8} = 0.973$ and $\varepsilon_{12} = 0.98$.

Figure 9 show the evolution of $\delta T_s$ as a function of $W$ for various values of $\delta W$. The results show that the minimum $\delta T_s$ corresponds to a values of $W$ near 1.7 g/cm$^2$ and maximum $\delta T_s$ corresponds to small and large values of $W$. The results also show that the variation of the error $\delta T_s$ is faster for large values of $\delta W$. We found for a value of $W = 3.7$ g/cm$^2$ and for a value of $\delta W = 1$ g/cm$^2$ that the $\delta T_s$ equals 1.59K. So we can conclude that the algorithm is very sensitive and requires real value of the TAWV. Thus a good estimation of the TAWV is the basis for an accurate estimation of LST from MSG-1 data.

Figure 10 illustrates the results obtained on the variation of the $\delta T_s$ as a function of the $\delta W$ for $W = 2$ g/cm$^2$. The results obtained show that $\delta T_s$ varies increasingly with $\delta W$. Indeed, we found that the variation of $W$ equals 0.1 g/cm$^2$ provides a variation of $\delta T_s$ equals 0.023K also a variation of $W$ equals 1.5 g/cm$^2$ provides a variation of $\delta T_s$ equals 0.5K.
Figure 9 - Probable LST estimation error due to the possible TAWV error as a function of the TAWV for various values of the possible TAWV error.

Figure 10 - Probable LST estimation error due to the possible TAWV error as a function of the possible TAWV error.
Sensitivity analysis to the viewing angle
To study the sensitivity of the proposed split-window algorithm to the viewing angle we consider that the TAWV equals $2 \text{g/cm}^2$. Also we consider that the surface emissivity $\varepsilon_{10.8} = 0.973$ and $\varepsilon_{12} = 0.98$. We have shown in Figure 11 the evolution of $\delta T_s$ as a function of the viewing angle $\theta$ for different values of the possible error on the viewing angle ($\delta \theta$). Clearly we note that $\delta T_s$ increasingly varies with $\theta$. It also increases rapidly with strong variations of $\theta$. The results show that the variation of $\theta$ equals $2^\circ$ causes a variation of $\delta T_s$ from $0 \text{K}$ to $0.023 \text{K}$. Furthermore, a variation of $\theta$ equals $10^\circ$ causes a variation of $\delta T_s$ from $0.004 \text{K}$ to $0.16 \text{K}$. From these data we can conclude that the proposed split-window algorithm is little sensitive to viewing angle against the surface emissivity and the TAWV.

Validation of the algorithm
To validate our algorithm two methods have been used:

Comparison with Sobrino and Romaguera’s algorithm data
We first calculated the brightness temperatures of channels IR10.8 and IR12 using the ‘Roberts’ model that we have coupled with data from six atmospheric profiles (Tropical, Mid-Latitude Summer, Mid-Latitude Winter, Sub-Arctic Summer, Sub-Arctic Winter and 1976 U.S. Standard). We then used these temperatures data to calculate the LST by two split-window algorithms: our proposed algorithm and the Sobrino and Romaguera’s algorithm (see the data part). Figure 12 shows the method of validation.

![Figure 11 - Probable LST estimation error due to the possible viewing angle error.](image-url)
For a brown loam surface type, we have shown in Figure 13 the comparison between the LST estimated by the proposed split-window algorithm and the LST calculated by the Sobrino and Romaguera’s algorithm. A number of situations were designed for the validation. For LST ($T_s = 270, 275, 280, 285, 290, 300, 305, 310, 315, 320, 325$ and $330\text{K}$) with 11 corresponding viewing angle ($\theta = 0, 5, 10, 15, 20, 25, 30, 35, 40, 45$ and $50^\circ$) were arbitrarily assumed for the simulation. The average accuracy obtained equals $0.45\text{K}$ and a root mean square error (RMSE) equals $0.79\text{K}$. The RMSE is computed as $\left[\sum (T_i - T) / N\right]^{1/2}$ ($T_i$ is retrieval temperature), and the average accuracy of land surface temperature is computed by $\left[\sum |T_i - T_s| / N\right]$ in which $N$ is the number of samples for the computation. We found also a standard deviation (SD) equals $0.76\text{K}$ and a correlation coefficient (R) equals 0.99. The comparison indicates that the accuracy is highest; therefore the results are acceptable and also encouraging.

Figure 12 - Schematic of the method validation.
Comparison with in-situ data

The best method to validate our proposed algorithm is compared with in-situ measurements, i.e. the comparison between the estimated LST and the measured LST at ground level. Therefore, we have represented in Figure 14 the comparison between the estimated LST by our proposed algorithm and the in-situ LST for the Kobou site (for more detail about the Kobou site see the in-situ data part). We have taken into account only the temperature values that satisfy condition $|T_s - T_i| < 10 - 15K$ in which $i$ is the channel IR10.8 or IR12 (because we have used in this work a first order Taylor expansion of the Planck function in the vicinity of the brightness temperature). We found acceptable results: a standard deviation SD equals 2.5 K and a correlation coefficient equals 0.94, we found also an average accuracy equals 1.96 K and a RMSE equals 2.75K. The same figure shows that there is a small difference between the calculations and measurements: Firstly, this difference is probably due to several factors such as the lack of knowledge of the average surface emissivity and of the TAWV. Secondly, it is very difficult to find an in-situ measurement corresponding to the size of the MSG-1 pixel ($3 \times 3km$).
**Spatial variation of land surface temperature in the Algiers-Mediterranean Sea border region**

Knowing the spatial variation of LST is necessary for the detection of sensitive areas that tend to desertification. In this work, we give an example of application of our algorithm. We have used our algorithm to find the spatial distribution of the surface temperature around the pixel of the region of Dar El-Beida. This pixel located in north-central Algeria (geographical coordinates 36.68°N and 3.21°E) at an altitude of 29 m, is characterized by a Mediterranean climate. We have used the proposed method in this particular region because it contents the ground and sea surface.

Using the proposed split-window algorithm we represented in Figure 15 the spatial distribution of the surface temperature after atmospheric corrections around the pixel of Dar El-Beida (on 15 March 2006 at 12:00). We considered that all pixels of the image have the same emissivity values and same values of TAWV, these values are considered equal to the value of the center pixel (Dar-El-Beida). The image is composed of 51 × 51 pixels with a spatial resolution of about 3km × 3km. The figure shows that the surface temperature of the ground is very variable with respect to the sea surface temperature. In this region, we found the surface temperature of the ground varies approximately from 293K to 308K and the sea surface temperature varies approximately from 287 K to 293 K.
**Conclusion**

The present study refers to the estimated LST from MSG-1 thermal infrared data. For the determination of the LST we found two principal problems: the atmospheric effect and the effect of surface emissivity. In order to correct these effects, a method called split-window was used. So, we have proposed a split-window algorithm to estimate the LST by using the two thermal infrared channels IR10.8 and IR12. The algorithm requires three essential parameters (TAWV, surface emissivity and viewing angle) for LST retrieval. Sensitivity analysis of the proposed algorithm indicates that the possible error of the viewing angle has relatively insignificant impact on the probable LST estimation error which is sensible to the possible error of surface emissivity and TAWV.

Two methods have been used to validate the proposed algorithm: for a brown loam surface type, we compared first the LST estimated by the proposed split-window algorithm with that calculated by the Sobrino and Romaguera’s algorithm. The results give an average accuracy equals 0.45K and a RMSE equals 0.79K. Then, we compared the LST estimated by the proposed split-window algorithm with in-situ measurement. The results give an average accuracy equals 1.96K and a root mean square error RMSE equals 2.75K. Therefore the results obtained are acceptable and also encouraging.

For the improvement of the algorithm, it is necessary to take into account the effects of the aerosol in the atmosphere because the aerosol absorbs, reflects and diffuses the radiation emitted by the soil and the atmosphere.
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