International Journal of Information & Network Security (IJINS)
Vol.2, No.1, February 2013, pp. 68~77
ISSN: 2089-3299

Split-Window LST Algorithms Estimation From AVHRR/NOAA Satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19) Using Gaussian Filter Function

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Article Info

Article history:

Received Sept 20th, 2012
Accepted Oct 21th, 2012

Keyword:

Land Surface Temperature
Split-window algorithm
MODTRAN 4.0
AVHRR/NOAA
Gaussian Filter Function.

ABSTRACT

A study has been carried out using MODTRAN 4.0 radiative transfer code simulations to calculate the brightness temperatures expected at the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration NOAA satellites series (7, 9, 11, 12, 14, 15, 16, 17, 18 and 19) by using Gaussian Referential Filter (GRF) and Gaussian Filter (GF) instead of filter Normalized Filter obtained from NOAA agency. The outputs of applying MODTRAN 4.0 are values of atmospheric parameters obtained by mathematical convolution using GRF and GF Filters. A detailed analysis of the total error in LST, $\delta_{Total(Ts)}$, in function of AVHRR/NOAA satellites, shows that the algorithms are able to estimate accurate LST between a minimum of 1.256 K and a maximum of 1.415 K with amplitude of about 0.159 K. The validations show also that the algorithms are capable to produce LST with a standard deviation lower than 1.554 K and a Root Mean Square Error (RMSE) lower than 1.558 K. This result gives the opportunity to use the filter GF instead of filter Normalized Filter obtained from NOAA agency, in other studies by creation of GF filters centered in any region of the electromagnetic.

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1. INTRODUCTION

Land Surface Temperature (LST) is one of the most key parameters in the physics of land surface processes, combining surface atmosphere interactions and the energy fluxes between the atmosphere and the ground surface [1-4]. It is used in many applications, such as evapotranspiration modeling [5-16], estimating soil moisture [17-22], and climatic hydrological and ecological studies [23-32]. An accurate LST retrieval also enables an analysis of the global surface temperature and its variability within a long period of time [33-36]. Some of the major research are related to the removal from remotely sensed data of the effects caused by atmospheric attenuation, land surface emissivity, and topography [37-47]. In 1998, Czajkowski et al. have started treating the influence of the Advanced Very High Resolution Radiometer (AVHRR) filter functions on surface temperature estimation from the Split-Window (SW) approach. In the present paper, an analysis of total error correction in pseudo-validation using MODTRAN simulation for Administration (NOAA) satellites series (7, 9, 11, 12, 14, 15, 16, 17, 18, 19) on the SW-LST algorithms performance has been carried out.

2. SW-LST Algorithms

The SW method was originally proposed to estimate Sea Surface Temperature (SST) from satellite measurements based on the differential absorption in two adjacent infrared channels, and then was extended to land surface. Many papers have used this technique to extract SST and LST [37;48-52]. Recent LST retrieval algorithms cited in the bibliography are based on the radiative transfer equation and the SW forms. The theory applied in these SW-LST algorithms can be found in [37;41;46;48;53-57;57]. In our case, the SW-LST algorithm structure proposed by Sobrino and Raissouni [53] has been used, which takes into account the emissivity and water vapor effects:

$$T_s = T_4 + c_1(T_4 - T_5) + c_2(T_4 - T_5)^2 + c_0 + (c_3 + c_4 W)(1-\varepsilon) + (c_5 + c_6 W)\Delta\varepsilon \quad (1)$$

where Ts is the surface temperature (in K), T4 and T5 are the at-sensor brightness temperatures of the AVHRR/NOAA thermal Channels 4 and 5 (in K), ε4 and ε5 are emissivity estimates for Channels 4 and 5, $\varepsilon = (\varepsilon_4 + \varepsilon_5)/2$ is the mean effective emissivity, $\Delta\varepsilon = (\varepsilon_4 - \varepsilon_5)$ is the emissivity difference, W (g cm^{-2}), is the total amount of the columnar atmospheric water vapor. Finally, c0 to c6 are the SW algorithm coefficients, obtained using MODTRAN 4.0 radiative code simulation [58].

3. MODTRAN 4.0 Simulations and Filter Functions

MODTRAN 4.0 radiative code is used to calculate the brightness temperatures expected at the AVHRR/NOAA satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19) thermal Channels 4 and 5 for 54 different atmospheric situations. The profiles of temperature for these situations were obtained from the radiosoundings extracted neatly from the Television InfraRed Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) Thermodynamic Initial Guess Retrieval (TIGR) database [59]. The calculations have been done for a large gradient of temperatures (i.e., T-5, T, T+5, T+10, and T+20, T is the first boundary layer temperature of the atmosphere), five different view angles (i.e., 0º, 10º, 20º, 30º and 40º), 54 atmospheric water vapor (W) values at nadir (i.e., Wmin = 0.15 g.cm-2 and Wmax = 4.65 g cm-2), and 100 emissivities of spectral responses of several types of surfaces extracted from the Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) spectral library [60].

The outputs of applying MODTRAN 4.0 radiative code are values of atmospheric parameters: atmospheric transmittance (τ), atmospheric downwelling radiance ($L_{atm}^{\downarrow}$) and atmospheric upwelling radiance ($L_{atm}^{\uparrow}$), obtained by mathematical convolution using filter functions corresponding to Channels 4 and 5 of AVHRR/NOAA satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19) for Normalized Filters.

The effective wavelength (λ_{eff} , in μm) (in Eq. 2) is a spectral channel corresponds to the maximum value of the filter function (*f*). Table 1, §5 shows the values of λ_{eff} corresponding to the considered AVHRR Channels 4 and 5.

$$\lambda_{eff} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} f(\lambda)\lambda d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} f(\lambda) d\lambda} \quad (2)$$

4. Numerical Coefficients and Sensitivity Analysis

The SW-LST algorithm coefficients c_i (i = 0, 1, 2, 3, 4, 5, 6) [see Eq. (1), § 2] were obtained from the minimization of 135000 simulation data (54 atmospheric profiles, 5 T values, 100 emissivities, 5 view angles) included in the constructed database for the AVHRR/NOAA satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19).

First, in order to quantify the impact of each error source on the SW-LST algorithm, a sensitivity analysis was carried out in order to examine the performance of the developed methodology under different meteorological conditions and land cover types. On the basis of the error theory, the following equation has been considered:

$$\delta_{Total}(T_s) = \sqrt{\delta_{alg}^2 + \delta_{NE\Delta E}^2 + \delta_{\varepsilon}^2 + \delta_W^2} \quad (3)$$

where δalg is the standard deviation associated with the algorithm and δNEΔT, δε and δW are the contribution to the total error due to the uncertainties for at-sensor temperatures, land surface emissivity and atmospheric water vapor, respectively, and they are given by:

$$\delta_{NE\Delta E} = \sqrt{\left(\frac{\partial T_s}{\partial T_4}\right)^2 e^2(T_4) + \left(\frac{\partial T_s}{\partial T_5}\right)^2 e^2(T_5)} \quad (4)$$

$$\delta_{\varepsilon} = \sqrt{\left(\frac{\partial T_s}{\partial \varepsilon_4}\right)^2 e^2(\varepsilon_4) + \left(\frac{\partial T_s}{\partial \varepsilon_5}\right)^2 e^2(\varepsilon_5)} \quad (5)$$

$$\delta_W = \left(\frac{\partial T_s}{\partial W}\right) e(W) \quad (6)$$

Thus, assuming typical values for the different errors, $e(T_4) = e(T_5) = 0.05$ K, $e(\varepsilon_4) = e(\varepsilon_5) = 0.005$ and $e(W) = 0.5$ g.cm^{-2}.

5. RESULTS AND ANALYSIS

5.1. AVHRR/NOAA satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19) SW algorithms coefficients gaussian referential and gaussian filter centred at the corresponding sensor effective wavelength

Table 1 shows the SW coefficients (c_0 to c_6) obtained from MODTRAN 4.0 radiative code simulations and statistical regressions that can be used to estimate LST from thermal infrared sensors of AVHRR/NOAA satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19). The calculations have been made using Gaussian Referential Filter (GRF) and Gaussian Filter (GF) centred at corresponding sensor effective.

The calculations have been made using the types of the spectral filter functions. Gaussian Referential Filter (GRF) and Gaussian Filter (GF) with the corresponding AVHRR Channels 4 and 5 effective wavelengths λ_{4eff} (μm) and λ_{5eff} (μm).

Table 1. Split-Window algorithm coefficients (c_0 to c_6) for AVHRR/NOAA satellites (7, 9, 11, 12, 14, 15, 16, 17, 18, 19) obtained using: Gaussian Referential Filter (GRF) and Gaussian Filter (GF) centred at corresponding sensor effective. Correlation coefficient (R).

NOAA	Filter	c_0 (K)	c_1	c_2 (K^{-1})	c_3 (K)	c_4 (K .cm^2.g^{-1})	c_5 (K)	c_6 (K .cm^2.g^{-1})	R
7	GRF	0.021	1.627	0.293	58.0	-0.33	-117	7.77	0.95
	GF	0.495	1.827	0.322	56.9	-0.20	-125	8.49	0.96
9	GRF	0.112	1.727	0.301	57.7	-0.34	-122	8.53	0.96
	GF	0.570	1.664	0.300	58.5	-0.51	-113	6.22	0.95
11	GRF	0.065	1.758	0.277	57.7	-0.19	-123	8.98	0.95
	GF	0.445	1.729	0.318	57.7	-0.36	-120	7.55	0.95
12	GRF	-0.003	1.701	0.290	56.7	0.06	-143	14.08	0.95
	GF	-0.110	1.266	0.308	60.0	-0.87	-107	6.03	0.93
14	GRF	-0.018	1.492	0.262	57.6	-0.17	-121	9.70	0.94
	GF	0.097	1.224	0.243	60.0	-0.83	-96	4.79	0.93
15	GRF	-0.061	1.587	0.302	57.4	-0.22	-124	9.75	0.95
	GF	0.065	1.182	0.259	61.1	-1.08	-89	2.85	0.93
16	GRF	-0.184	1.570	0.326	56.1	0.14	-164	18.77	0.94
	GF	-0.185	1.338	0.288	60.0	-0.71	-117	8.38	0.93
17	GRF	-0.059	1.587	0.284	57.6	-0.20	-122	9.29	0.95
	GF	0.265	1.521	0.274	59.1	-0.59	-108	6.06	0.94
18	GRF	-0.133	1.304	0.251	57.6	-0.27	-118	10.10	0.94
	GF	0.127	1.228	0.236	59.3	-0.69	-102	6.34	0.94
19	GRF	-0.168	1.299	0.231	57.2	-0.10	-121	11.30	0.94
	GF	0.227	1.276	0.237	58.4	-0.49	-108	7.87	0.94

The sensitivity analysis results (Table 2), show a small variation amplitude of about 0.03 K in the error due to the minimization, δ_{alg} (in K), with values varying between a minimum of 1.04 K and a maximum of 1.07 K. The error due to the noise equivalent delta temperature, $\delta_{NE\Delta T}$, is varying with amplitude of about 0.30 K between a minimum of 0.22 K and a maximum of 0.08 K. The error due to the uncertainty of the atmospheric water vapor content, δ_w, shows variation amplitude of about 0.14 K between a minimum of 0.02 K and a maximum of 0.16 K.

The error due to the uncertainty of the surface emissivity, δ_ε, shows variation amplitude of about 0.26 K with a minimum of 0.62 K and a maximum of 0.88 K. Finally, The total error in the LST, $\delta_{Total(Ts)}$, is showing variation amplitude of about 0.159 K with a minimum of 1.256 K and a maximum of 1.415 K.

Table 2. The effective wavelengths λ_{4eff} (μm) and λ_{5eff} (μm) for the SW AVHRR Channel 4 and 5. δ_{alg} error due to the minimization, $\delta_{NE\Delta T}$ error due to the noise equivalent delta temperature, δ_ε error due to the uncertainty of the surface emissivity, δ_w error due to the uncertainty of the atmospheric water vapor content, and $\delta_{Total(Ts)}$ the total error in the LST .

NOAA	λ_{4eff} (μm)	λ_{5eff} (μm)	δ_{alg} (K)	$\delta_{NE\Delta T}$ (K)	δ_ε (K)	δ_W (K)	$\delta_{Total}(T_s)$ (K)
7	10.79	11.9	1.05	0.27	0.73	0.02	1.307
			1.04	0.3	0.77	0.02	1.331
9	10.774	11.85	1.04	0.28	0.74	0.03	1.307
			1.05	0.27	0.72	0.02	1.302
11	10.794	11.891	1.05	0.28	0.75	0.03	1.321
			1.05	0.28	0.75	0.02	1.321
12	10.857	11.945	1.05	0.28	0.8	0.08	1.352
			1.07	0.24	0.68	0.02	1.290
14	10.81	11.982	1.06	0.25	0.72	0.04	1.306
			1.07	0.22	0.63	0.02	1.261
15	10.82	11.926	1.05	0.27	0.74	0.04	1.313
			1.07	0.22	0.62	0.02	1.256
16	10.914	11.977	1.06	0.28	0.88	0.16	1.415
			1.07	0.24	0.72	0.03	1.312
17	10.797	11.927	1.06	0.27	0.73	0.03	1.315
			1.06	0.26	0.69	0.02	1.291
18	10.797	12.016	1.06	0.23	0.69	0.05	1.287
			1.06	0.22	0.64	0.02	1.258
19	10.793	12.045	1.06	0.23	0.7	0.06	1.292
			1.06	0.22	0.66	0.03	1.268
		MIN	1.04	0.22	0.62	0.02	1.256
		MAX	1.07	0.30	0.88	0.16	1.415
		|MAX-MIN|	0.03	0.08	0.26	0.14	0.159
		MEAN	1.06	0.26	0.72	0.04	1.305

The comparison between the different SW is shown; the behavior of the algorithms in terms of their errors can be seen. The results show also that the spectral band passes of the two long-wave sensors (AVHRR Channel 4 and Channel 5 of AVHRR/NOAA Series) vary significantly. particularly for each filter.

The result show a small error on LST if the algorithm was applied to the AVHRR/NOAA new generation (NOAA-14, 15, 17 , 18 and 19 SW algorithm retrieves LST more accurately than other AVHRR/NOAA series).

An accuracy LST SW algorithm must provide the LST more accurately and give less sensitive to uncertainties in our knowledge of land surface emissivities and atmospheric water vapor content. and to the instrument noise.

5.2. SW Generalized sw algorithm

A generalized SW algorithm specifically using to retrieve LST from AVHRR/NOAA series (7. 9. 11. 12. 14. 15. 16. 17. 18 and 19). can be estimated by using two filter functions. In order to apply the filter function. we followed two procedures to build up the corresponding reliable function filter Generalized NOAAs - Gaussian Filter (G-GF): centered at the corresponding effective wavelength average (λ_{eff}).

Table 3 compiles the Generalized SW coefficients (c_0 to c_6) obtained from MODTRAN 4.0 radiative code simulations and statistical regressions for AVHRR/NOAA satellites. Gaussian Filter (GF) centred at corresponding sensor effective.

Table 3. Generalized Split-Window coefficients (c_0 to c_6) for Generalized NOAA Series Gaussian Filter (G-GF). Correlation coefficient (R).

Generalized SW	c_0 (K)	c_1	c_2 (K^{-1})	c_3 (K)	c_4 (K $.cm^2.g^{-1}$)	c_5 (K)	c_6 (K $.cm^2.g^{-1}$)	R
G-GF	0.13	1.35	0.27	59.5	-0.71	-103	5.56	0.94

Table 4 shows the corresponding results with total errors lower to $\delta_{Total(Ts)}$ = 1.774 K . with the major contribution to the total error being the uncertainty in the ε. assumed to be 0.5% for G-GF.

The algorithm can be used to calculate the LST for each AVHRR/NOAA series (7. 9. 11. 12. 14. 15. 16. 17. 18 and 19) with total errors ($\delta_{Total(Ts)}$) lower than 1.774 K .

Table 4. The effective wavelengths λ_{4eff} (μm) and λ_{5eff} (μm) for the SW AVHRR Channel 4 and 5. The effective wavelength difference between AVHRR Channel 4 and Channel 5: $\Delta\lambda = \lambda_{5eff} - \lambda_{4eff}$ μm. Correlation coefficient (R). The sensitivity analysis: Error due to the minimization (δ_{alg}). Error due to the noise equivalent delta temperature ($\delta_{NE\Delta T}$). Error due to the uncertainty of the surface emissivity (δ_{ε}). Error due to the uncertainty of the atmospheric water vapor content (δ_w). and total error in the Land Surface Temperature ($\delta_{Total}(T_s)$) .

Generalized SW	λ_{4eff} (μm)	λ_{5eff} (μm)	δ_{alg} (K)	$\delta_{NE\Delta T}$ (K)	δ_{ε} (K)	δ_W (K)	$\delta_{Total}(T_s)$ (K)
G-GF	1.06	0.24	1.33	0.67	0.02	1.718	1.277

5.3. Validation data

We do not have a complete data set of in situ measurements coinciding with all the platforms; thus. we provide a pseudo-validation of AVHRR/NOAA series (7. 9. 11. 12. 14. 15. 16. 17. 18 and 19) using some in situ measurements of LST in coincidence with NOAA 11 and NOAA 12 and total error in the LST. δTotal(Ts) NOAA Y/ NOAA 11.12.

In order to give an idea of the approximated behavior of the proposed SW algorithms. we have used the database given by Prata (1994). Table 5 describes the conditions in term of water vapor. emissivity. temperature and number of data for Hay and Walpeup in Australia.

Table 5. Atmospheric water vapor content (W) at nadir view ($g.cm^{-2}$). Emissivity (ε) and Land Surface Temperature (LST) Statistics for Hay and Walpeup in situ measurement sites for NOAA 11 and NOAA 12.

	Hay and Walpeup (NOAA 11)	Hay and Walpeup (NOAA 12)
$W_{min\ (g.cm^{-2})}$	0.84	0.84
$W_{max\ (g.cm^{-2})}$	1.18	1.18
$W_{mean\ (g.cm^{-2})}$	0.95	0.94
LST_{min} (K)	272.35	272.35
LST_{max} (K)	318.80	297.55
LST_{mean} (K)	286.28	280.42
ε_{min}	0.978	0.978
ε_{max}	0.989	0.980
ε_{mean}	0.980	0.979
# data	191	118

Table 6 gives validation of the proposed SW algorithms for NOAA 11 and 12 using Hay and Walpeup in situ measurements data and behavior study of the pseudo-validation of SW algorithms for NOAA (7, 9, 14, 15, 16, 17, 18, 19) using (G-NF) and (G-GF) Filters.
The results show that the algorithms are capable to produce LST AVHRR/NOAA series with a standard deviation lower than 1.554 K and a Root Mean Square Error (RMSE) lower than 1.558 K.

Table 6. Validation of the proposed Split-Window (SW) algorithms for NOAA 11 and 12 using Hay and Walpeup in situ measurements data and behavior study of the pseudo-validation of SW algorithms for NOAA (7, 9, 14, 15, 16, 17, 18, 19) using Generalized NOAA Series Filter (G-NF). Generalized NOAA Series Gaussian Filter (G-GF. General statistics: Minimum (Min). Maximum (Max). Average (μ) and Standard deviation (σ). The effective wavelengths λ_{4eff} (μm) and λ_{5eff} (μm) for the SW AVHRR Channel 4 and 5. The effective wavelength difference between AVHRR Channel 4 and Channel 5: $\Delta\lambda = \lambda_{5eff} - \lambda_{4eff}$ μm. Mean differences (bias) (K). Standard deviation of differences (K). Root Mean Square Error (K)

		GRF			GF		
Sites	**Sensor**	**Mean differences (K)**	**Standard deviation (K)**	**Root Mean Square Error (K)**	**Mean differences (K)**	**Standard deviation (K)**	**Root Mean Square Error (K)**
Hay and Walpeup (NOAA11)	NOAA 7	0.755	1.470	1.425	0.758	1.451	1.436
	NOAA 9	0.541	1.548	1.544	0.539	1.554	1.558
	NOAA 11	0.654	1.489	1.458	0.661	1.525	1.527
	NOAA 12	0.683	1.457	1.425	0.685	1.471	1.459
	NOAA 14	0.845	1.401	1.387	0.843	1.365	1.374
	NOAA 15	0.811	1.456	1.471	0.758	1.458	1.447
	NOAA 16	0.799	1.389	1.401	0.895	1.399	1.411
	NOAA 17	0.845	1.457	1.448	0.799	1.458	1.469
	NOAA 18	1.119	1.333	1.345	1.108	1.348	1.354
	NOAA 19	1.218	1.354	1.361	1.214	1.362	1.370
Hay and Walpeup (NOAA12)	NOAA 7	1.169	1.202	1.197	1.158	1.201	1.191
	NOAA 9	1.012	1.311	1.285	1.017	1.274	1.269
	NOAA 11	1.025	1.301	1.269	1.061	1.239	1.250
	NOAA 12	1.112	1.188	1.174	1.099	1.181	1.165
	NOAA 14	1.117	1.158	1.139	1.188	1.141	1.158
	NOAA 15	1.169	1.188	1.148	1.116	1.178	1.184
	NOAA 16	1.295	1.114	1.121	1.286	1.101	1.107
	NOAA 17	1.152	1.158	1.166	1.177	1.145	1.135
	NOAA 18	1.125	1.117	1.109	1.342	1.101	1.103
	NOAA 19	1.124	1.112	1.091	1.454	1.084	1.079

6. CONCLUSION

The study result gives the opportunity to use Gaussian Referential Filter (GRF) and Gaussian Filter (GF) instead of Normalized Filters obtained from NOAA agency, to retrieve the precise SW-LST from satellite thermal data.

The SW-LST algorithm coefficients c_i (i = 0. 1. 2. 3. 4. 5. 6) were obtained from the minimization of 135000 simulation data (54 atmospheric profiles. 5 T values. 100 emissivities. 5 view angles) for the AVHRR/NOAA satellites (7. 9. 11. 12. 14. 15. 16. 17. 18. 19). The calculations have been made using Gaussian Referential Filter (GRF) and Gaussian Filter (GF) with the corresponding AVHRR Channels 4 and 5 effective wavelengths λ_{4eff} (μm) and λ_{5eff} (μm). with the corresponding AVHRR Channels 4 and 5 effective wavelengths. The total error in LST. $\delta_{Total(Ts)}$. is showing a variation amplitude of about 0.159 K with a minimum of 1.256 K and a maximum of 1.415 K.

ACKNOWLEDGEMENTS

This work was supported in part by the Ministry for Higher Education, Management Training and Scientific Research under CSPT Grants for Integration and application of GIS and GPS on mobile systems and Ad-hoc wireless sensor networks for remote sensing algorithm validation projects.

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