An angular-dependent split-window equation for SST retrieval from off-nadir observations

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***Abstract*— An angular-dependent split-window equation is proposed for determining the Sea Surface Temperature (SST) at any observation angle, including large viewing angles at the image edges of satellite sensors with wide swaths. The proposed equation takes into account the angular dependences of the atmospheric correction and also the emissivity correction. An explicit dependence on the SSE is considered in an independent term. The inclusion of such a term is not common in the current operational SST algorithms but we consider it appropriate taking into account the non-blackness of the sea surface emission for large angles and also the dependence on wind speed.**

The equation has been adapted to the Moderate Resolution Imaging Spectrometer (MODIS) on board EOS-Terra and EOS-Aqua, with at surface observation angles up to 65º, and to the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board MSG, with even larger observation angles. Angular-dependent coefficients were estimated for the atmospheric and emissivity terms using synthetic data generated from a series of cloud-free, latitude-equally distributed radiosounding profiles. The use of the proposed expression requires as input data: at-sensor brightness temperatures for the split-window bands, the observation angle at each pixel, an estimate of the water vapor content and accurate SSE values for both channels. A comparison of the results of the equation for MODIS with in-situ measurements gathered from different NOAA ships and buoys placed around the world showed an accuracy of about ± 0.3 K for any observation angle, including off-nadir viewings, while the MODIS operational algorithm leaded to an error of ± 0.7 K at large angles. The proposed technique is mainly recommended to retrieve SST from observations at large viewing angles, since similar values are obtained by the current operational algorithms for nadir viewings.

Sea surface temperature; split-window equation; sea surface emissivity; MODIS-EOSTerra/Aqua; SEVIRI-MSG.

I. INTRODUCTION

The accuracy currently required for Sea Surface Temperature (SST) determination for climate and oceanographic applications was defined as ± 0.3 K. However, the SST error obtained with the current algorithms usually increases with the satellite angle of observation. Some of the current satellite sensors have wide swath in the across-track direction, with large observation angles near the image edges. This is the case of instruments such as the Moderate Resolution Imaging Spectrometer (MODIS) on EOS Terra/Aqua platforms, and the Advanced Very High Resolution Radiometer (AVHRR/3) on board NOAA 17/18 and MetOp, but also of geostationary satellites such as the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board Meteosat Second Generation (MSG). This paper proposes a split-window equation that takes into account the angular dependence of the atmospheric correction, due to the increase of the atmospheric path with viewing angle, and of the emissivity correction, due to the reduction of SSE with increase of angle. The objective is to develop global split-window algorithms suitable for retrieving accurate SSTs from observations carried out at any angle, with special interest paid to off-nadir viewings in order to make use of all the available satellite data. For that purpose, we consider important the introduction of an explicit dependence on the Sea Surface Emissivity (SSE), which is common for land surface temperature retrievals but not for the SST operational algorithms.

II. THE SPLIT-WINDOW EQUATION

The proposed algorithm follows the model of Coll and Caselles [1], which incorporates separate terms for the atmospheric and emissivity corrections:

$$T=T_i+ a\,(T_i-T_j) + b\,(T_i-T_j)^2 + c + B(\varepsilon) \qquad (1)$$

where T is the surface temperature, and T_i and T_j are the brightness temperatures in the split-window channels (two bands placed within the atmospheric window 10-12.5μm) . *a*, *b*, and *c* can be considered as the atmospheric split-window coefficients and are independent of the surface [1] (See Section III). This algorithm assumes a quadratic dependence on the brightness temperature difference T_i-T_j, since the original linear function showed dependence on the atmospheric conditions and a quadratic function was considered better as a global algorithm. Emissivity effects are compensated by the term B(ε). This term depends on the average SSE, $\varepsilon=(\varepsilon_i+\varepsilon_j)/2$, and the SSE difference, $\Delta\varepsilon= \varepsilon_i-\varepsilon_j$, for both split-window channels:

$$B(\varepsilon)=\alpha(1-\varepsilon)-\beta\Delta\varepsilon \qquad (2)$$

where α and β depend on the atmospheric properties and the surface temperature (see Section IV).

This work has been supported by the Spanish Ministerio de Educación y Ciencia (projects CGL2005-24207-E/CLI, CGL2005-03386 and CGL2006-27067-E/CLI, and the “Juan de la Cierva” Research contract of Dr. R. Niclòs).

The study of the dependences of these terms and the assessment of coefficients for the case of the SST retrieval was carried out with synthetic data generated from the SAFREE database using the radiative transfer code MODTRAN 4 [2]. The SAFREE database is a cloud-free, latitude equally distributed database of 402 marine atmospheric profiles collected from 1979 to 1997. François et al. [3] proved that the SAFREE database is suitable to develop global SST algorithms and pointed out that simulation-based SST retrievals are feasible and accurate when sufficient care is taken in the constitution of the training atmospheric database. Top-of-atmosphere spectral radiances were calculated using the 402 SAFREE profiles, for 7 observation angles from 0º to 65º, 4 surface wind speed values (taking into account the SSE dependence on wind speed, following the model given by [4]), and assuming 3 SST values for each radiosounding: T_0, T_0+3K, and T_0-3K, T_0 being the temperature of the first level of the profile [5]. Consequently, 33,768 simulation cases were considered, obtaining spectral radiances from 600 to 3,000 cm^{-1} for each case. Finally, these spectra were integrated for the split-window bands, obtaining the T_i and T_j required in order to study the terms of equations (1) and (2).

III. THE ATMOSPHERIC CORRECTION

The split-window technique takes advantage of the different absorption between two bands placed within the atmospheric window 10-12.5 µm (e.g. bands 31 and 32 of MODIS-EOSTerra/Aqua or bands 9 and 10 of SEVIRI-MSG), which is closely correlated with atmospheric conditions, mainly the water vapor and air temperature profiles. Surface-independent coefficients were calculated by means of a regression analysis between SST-T_i and T_i-T_j, where the top-of-atmosphere brightness temperatures, T_i and T_j, are obtained considering the surface as a black-body (ε=1 and $\Delta\varepsilon$=0). For a given observation angle, the different atmospheric absorption produced by the water vapor content of each radiosounding is the major cause of the temperature differences. However, the atmospheric correction for a given atmospheric profile increases with the observation angle as a consequence of the atmospheric path enlargement (i.e. the airmass increases a length sec(θ)-1 for a sensor observation angle *θ*). Taking into account the higher increase in SST- T_i than in T_i – T_j with angle (see Fig. 1), an angular dependence of the atmospheric coefficients is required to fit these differences at any angle. The analysis of the effect of modifying the observation angle for the SAFREE profiles showed that the atmospheric coefficients are angular dependent and can be expressed as a linear function of S= sec(θ)-1 [5].

Therefore, (1) is rewritten as:

$$SST=T_i+(a_1S+a_2)(T_i-T_j)+(b_1S+b_2)(T_i-T_j)^2+(c_1S+c_2)+B(\varepsilon) \quad (3)$$

IV. THE EMISSIVITY CORRECTION

The novelty of the paper is the use of explicit dependences of the proposed SST equation on the SSE values integrated for the split-window bands. The SSE decreases with observation angle, but also with the surface wind speed. There is a SSE reduction of about 5 % at 11 µm and over 7 % at 12 µm from 0º to 65º, as shown by experimental data [6] and models [4].

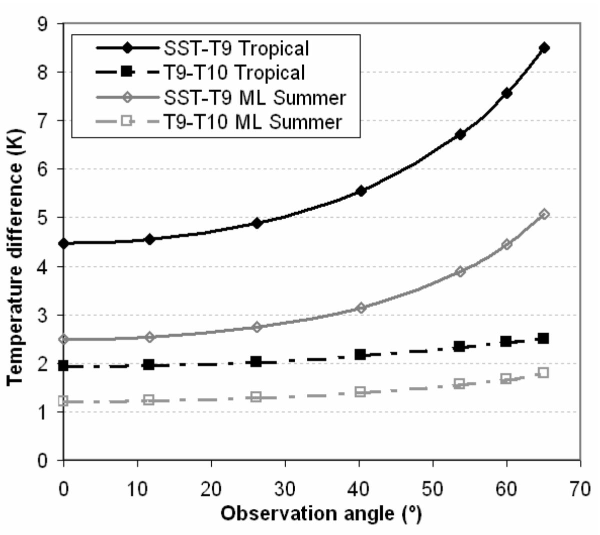

Figure 1. Effect of the observation angle on the atmospheric correction: Angular variation of the temperature differences SST-T_9 and T_9-T_{10} for the SEVIRI-MSG channels and two standard atmospheres.

For example, values of 0.943 (0.941) and 0.915 (0.919) are obtained at 65º for channels 31 and 32 of MODIS (9 and 10 SEVIRI), respectively. Therefore, within MODIS and SEVIRI images, the range of variability of the SSEs with the observation angle is comparable to the variation shown by other natural emitting surfaces, such as soils and vegetation, at nadir. Taking into account the non-blackness of the sea surface in this case, we consider appropriate the introduction of the explicit dependence on the SSE, given by (2), in the SST split-window algorithm, similar to that proposed by [1] for land surface temperature estimates. The expressions for the coefficients of this term were adapted for the sea surface, changing from Lambertian reflection for land surfaces to a specular reflection for sea surfaces:

$$\alpha(\theta)=(d_i(\theta)-d_j(\theta))*A(\theta)*\tau_j(\theta)+d_i(\theta) \quad (4)$$

$$\beta(\theta)=A(\theta)*\tau_j(\theta)*d_j(\theta)+\alpha(\theta)/2 \quad (5)$$

where $d_k(\theta)$ is defined for a channel k as:

$$d_k(\theta)=\frac{T_{k,SURF}(\theta)}{n_k}+\left[\frac{n_k-1}{n_k}T_{k,SURF}(\theta)-T_k{}^{\downarrow}{}_{atm}(\theta)\right]*(1-\tau_k(\theta)) \quad (6)$$

n_k is a radiometric parameter that depends on the spectral band, which is obtained from the potential approximation of the Planck function: $B_k(T)=m_k\ T^{n_k}$. The coefficients for this expression were calculated for MODIS Terra/Aqua channels (n_{31}=4.61800/4.61513 ± 0.00012 and n_{32}= 4.24992/4.24668 ± 0.00010), and SEVIRI-MSG channels (n_9=4.71555±0.00013 and n_{10}=4.28275±0.00010). The effective atmospheric temperature in the downward direction, $T_k{}^{\downarrow}{}_{atm}(\theta)$, was defined from the Planck radiance as $B_k\left(T_k{}^{\downarrow}{}_{atm}(\theta)\right)=L_k{}^{\downarrow}{}_{atm}(\theta)/(1-\tau_k(\theta))$. Term A is considered angle and temperature-dependent, and thus A(θ)= *a(θ)* + *b(θ)* (T_i-T_j) in (4)-(5). The surface temperature $T_{k,SURF}(\theta)$ is obtained from the surface radiance integrated for channel k and inverted by means of the Planck function weighted by the filter response function. α and β depend on the atmospheric properties through $T_{k}^{\downarrow}{}_{atm}(\theta)$, $\tau_k(\theta)$ and $A(\theta)$, and so they should depend on the column water vapor content and the observation angle. However, Niclòs et al. [5] concluded that the angular dependence can be neglected in this case, but not the dependence on the water vapor content, which was considered as a function of the oblique column water vapor content, W, defined as $W=W_0/\cos(\theta)$. Quadratic functions were obtained from regression analyses of α and β against W, the dependence of β being much more important than the one of α. Therefore, (2) can be rewritten as:

$$B(\varepsilon)=[\alpha_0+\alpha_1 W+\alpha_2 W^2](1-\varepsilon)-[\beta_0+\beta_1 W+\beta_2 W^2]\Delta\varepsilon \quad (7)$$

V. RESULTS

The proposed split-window equation (given by (3) and (7)) was first adapted for the MODIS sensors on board EOS-Terra and EOS-Aqua [5]. However, the application of this technique to the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board MSG (with a swath width of 2330 km and observation angles up to nearly 80°) seems to be crucial. Tables I and II give the coefficients retrieved for both sensor using the simulation database generated from the SAFREE atmospheric profiles with the MODTRAN 4 code. Notice that slightly different coefficients were obtained for MODIS on board EOS Terra and EOS Aqua due to the small differences in the filter response functions. The use of the proposed equations requires as input data: at-sensor brightness temperatures for the split-window bands (sub-index i and j are 31 and 32 for MODIS, and 9 and 10 for SEVIRI, respectively), the observation angle at each pixel, accurate SSE values for the split-window channels and an estimate of the water vapor content.

A. Sea surface emissivity determination

The SSE values for the split-window channels, ε_i and ε_j, required to compute $\varepsilon=(\varepsilon_i+\varepsilon_j)/2$ and $\Delta\varepsilon=\varepsilon_i-\varepsilon_j$, can be determined using the model proposed in [4]. This model is a physical characterization of the sea surface emission, including the reflected emission, but it is mathematically complex. We developed a simple parametrization based on values computed by this model to calculate accurate SSEs as a function of the surface wind speed, U, and the observation angle, θ [7]. A simple equation $\varepsilon_k(\theta,U)=\varepsilon_k(0^\circ)\,[\cos(\theta^{(cU+d)})]^{b_k}$ allows the determination of SSE, $\varepsilon_k(\theta,U)$, from its value at nadir, $\varepsilon_k(0^\circ)$ (0.99229/0.99229 and 0.98823/0.98813 for MODIS Terra/Aqua channels 31 and 32, respectively, and 0.99176 and 0.98875 for SEVIRI channels 9 and 10), using only three coefficients: c = -0.037 s/m, d = 2.36, and b_k being dependent on the spectral band (b_{31}=0.0342/0.0342 and b_{32}=0.0506/0.0508 for MODIS Terra/Aqua, and b_9=0.0347 and b_{10}=0.0483 for SEVIRI). We suggest this parametrization as an operative and simple alternative in order to generate accurate SSE imagery for a further retrieval of SST.

The effect of surface wind speed is important for observation angles of over 55-60° [4], and consequently the use of this parametrization with wind satellite imagery could improve the SSE estimates, and so SST retrievals, for such angles. However, a preliminary study shows that there are some limitations for the synergy of satellite thermal and wind speed data. There is a difference in the spatial resolution, with pixel size of about 25km^2 for the wind speed data obtained by sensors such as AMSR-E on board EOS-Aqua or SeaWinds on QuikSCAT. However, the main problem is to obtain concurrent thermal and wind data. Although this problem seemed solved for the EOS-Aqua, with MODIS and AMSR-E sensors in the same platform, pixels of MODIS imagery observed at angles from 55° to 65° are not overlapped with wind data, since the maximum angle of coincidence for MODIS and AMSR-E is 55°. The overlapping problem is even worse for sensors such as AATSR and ASAR on ENVISAT. In the case of SEVIRI data, the range of angles for which the wind speed has an important effect is even larger. However, the synergy of thermal and wind data only can be possible for the SEVIRI image areas concurrent with images of wind speed of sensors on board other platforms, limiting the correction of the wind effect on SST to the availability of wind information and so to the frequency of radar sensors. This fact should be taken into account for the design of future missions.

B. Estimate of the water vapor content

An estimate of the total column water vapor content, $W=W_0/\cos(\theta)$, improves the SST results according to [5]. W_0 can be obtained with an uncertainty of ± 10% from MOD07 or MYD07 level-2 products of MODIS Terra and Aqua, respectively. These products give temperature and water vapor profiles from which the W_0 is obtained.

TABLE I. ATMOSPHERIC CORRECTION COEFFICIENTS OF (3)

Sensor-Platform	a_1	a_2	b_1	b_2	c_1	c_2
SEVIRI-MSG	0.00±0.02	1.434±0.015	0.171±0.006	0.301±0.005	0.373±0.014	0.269±0.005
MODIS-EOSTerra	0.03±0.02	2.57±0.02	0.359±0.011	0.427±0.009	0.466±0.012	0.392±0.006
MODIS-EOSAqua	0.02±0.02	2.54±0.02	0.357±0.011	0.419±0.009	0.466±0.012	0.396±0.006

TABLE II. EMISSIVITY CORRECTION COEFFICIENTS OF (7)

Sensor-Platform	α_0	α_1	α_2	β_0	β_1	β_2
SEVIRI-MSG	55.34±0.05	-2.18±0.02	-0.127±0.002	121.79±0.15	-19.52±0.07	0.883±0.007
MODIS-EOSTerra	53.23±0.05	-1.27±0.02	-0.210±0.002	196.1±0.2	-35.74±0.10	1.785±0.010
MODIS-EOSAqua	53.36±0.05	-1.27±0.02	-0.211±0.002	194.9±0.2	-35.56±0.10	1.779±0.010

An estimate of the water vapor content concurrent with SEVIRI imagery can be obtained using a combination of the brightness temperatures in the thermal infrared region. However, methods proposed assuming a blackbody emissivity for the sea surface are not suitable for the SEVIRI, since such an approximation is not right for large observation angles. The blackbody assumption permits the use of the relationship $\tau_k=(T_k-T_{k,atm})/(SST-T_{k,atm})$ (i.e. $T_k=SST\tau_k+T_{k,atm}(1-\tau_k)$), which is the basic statement of several methods for obtaining the W over sea surfaces, even from SEVIRI data. However, we consider necessary the development of new methodologies that take into account the non-blackness of the sea emission, or the adaptation of methods proposed for obtaining the W over land surfaces. This study is being done at the moment and it will be the purpose of a future work.

VI. VALIDATION

A set of 61 matchups of MODIS imagery and *in situ* measurements were used in order to check the suitability of the proposed equation. Taking into account the changes in the radiometric accuracy of MODIS Terra data, only imagery from after October 2000 were used for the validation. *In situ* temperature and wind speed data were measured from NOAA buoys and ships, and only data with wind speed larger than 6m/s were used since in such case the SST can be obtained from bulk SST measurements minus a constant value (0.2K approx.). The total column water vapor content was obtained from the MOD07 product. A wide range of latitude, water vapor content, and SST values were considered in the validation, trying to obtain a global coverage [5]. In addition, data measured at observation angles well-distributed between 0º and 65º were used. Table III shows the results of the validation process for the proposed MODIS-EOSTerra algorithm in comparison with the results obtained using the MOD28 SST product. This product provides SST values using the operational MODIS algorithm [8], which does not have the SSE as an input. Results are also shown separately for observation angles larger and lower than 40º. The figures of Table III (statistically meaningful) show the good soundness of the proposed equation for any observation angle, achieving an accuracy of ± 0.3 K even for large angles, and so reducing the error with respect to the MOD28 product for the off-nadir views at the edges of MODIS Terra images (± 0.7 K).

VII. CONCLUSIONS

An angular-dependent split-window equation with an explicit dependence on the SSE has been proposed for SST retrieval in order to improve the results for observation at large viewing angles. The coefficients of this equation have been determined for the MODIS on board EOS-Terra and EOS-Aqua platforms and for the SEVIRI on MSG. A validation study showed the soundness of this equation, which is mainly recommended when a user needs to retrieve SST for a study area located at the edges of MODIS imagery or at SEVIRI image sections observed at large angles.

TABLE III. VALIDATION RESULTS FOR MODIS

Observation angle		**$SST_{algorithm} - SST_{in\ situ}$ (K)**	
		Proposed algorithm	*MOD28*
All angles (61 cases)	*Bias*	-0.14	0.4
	σ	0.3	0.4
	RMSE	0.3	0.6
$\theta \leq 40$ deg (39 cases)	*Bias*	-0.3	0.3
	σ	0.3	0.3
	RMSE	0.4	0.4
$\theta > 40$ deg (22 cases)	*Bias*	0.07	0.6
	σ	0.3	0.4
	RMSE	0.3	0.7

σ=standard deviation, RMSE=root-mean square error.

ACKNOWLEDGMENT

We thank the EOS Data Gateway for providing the satellite images, and the National Oceanographic Data Center (NODC), the National Data Buoy Center (NDBC) of the NOAA, and the Spanish *Ministerio de Fomento* for supplying *in situ* data. We would like also to show gratitude for the assistance of Dr. François (Université Paris-Sud) and Dr. Le Borgne (CMS, Météo-France), who provided us with the SAFREE database.

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