A Simplified Method for Estimating the Total Water Vapor Content Over Sea Surfaces Using NOAA-AVHRR Channels 4 and 5

J. A. Sobrino, J. C. Jimenez, N. Raissouni, and G. Soria

***Abstract*—A simplified method for estimating the total amount of atmospheric water vapor, W, over sea surfaces using NOAA-AVHRR Channels 4 and 5 is presented. This study has been carried out using simulated AVHRR data at 11 and 12 μm (with MODTRAN 3.5 code and the TIGR database) and AVHRR, PODAAC, and AVISO databases provided by the Louis Pasteur University (Strasbourg-France), NASA-NOAA, and Météo France, respectively. The method is named *linear atmosphere–surface temperature relationship* (LASTR). It is based on a linear relationship between the effective atmospheric temperature in AVHRR Channel 4 and sea surface temperature. The LASTR method was compared with the linear split-window relationship (LSWR), which is based on a linear regression between W and the difference of brightness temperature measured in the same channels ($\Delta T = T_4 - T_5$). The results demonstrate the advantage of the LASTR method, which is capable of estimating W from NOAA-14 afternoon passes with a bias accuracy of 0.5 g cm^{-2} and a standard deviation of 0.3 g cm^{-2}, compared with the W obtained by the AVISO database. In turn, a global bias accuracy of 0.1 g cm^{-2} and a standard deviation within 0.6 g cm^{-2} have been obtained in comparison with the W included in the PODAAC database derived from the special sensor microwave/imager (SSM/I) instrument.**

***Index Terms*—AVHRR, PODAAC, water vapor.**

I. Introduction

The total atmospheric water vapor (W) is an important component for the study of the hydrological cycle and the Earth's climate [1]. Efforts have been made by numerous researchers to estimate W over land and ocean surfaces using AVHRR thermal infrared and special sensor microwave/imager (SSM/I) microwave remote sensing data. In recent years the microwave remote sensing techniques have been developed to retrieve the columnar water vapor over the oceans with a root mean square accuracy of 0.12 g cm^{-2} with a spatial resolution of 50 km [2]. Our objective in this research is to estimate W over sea surfaces with a spatial resolution of 1 km using AVHRR data. Sobrino *et al.* [3] presented a technique called split-window covariance–variance ratio (SWCVR), based on a quadratic relationship between W and the ratio of the spatial covariance and variance of brightness temperatures measured in channels 4 (T_4) and 5 (T_5) of AVHRR in subsets of N neighboring pixels. The SWCVR enables us to obtain W from AVHRR data over land surfaces with a standard error of 0.5 g cm^{-2} [4]. The main shortcoming of the SWCVR technique is that, due to its mathematical structure, it should be applied over regions with a certain level of thermal heterogeneity (we recommended a standard deviation of T_4 in the subset $>$ 0.5 K). Therefore, it does not work in most situations over sea surfaces. To solve this problem we are proposing a simplified technique, named *linear atmosphere–surface temperature relationship* (LASTR), based on a linear correlation between the effective atmospheric temperature in AVHRR Channel 4 and the sea surface temperature (SST). This method is also compared for a cloud-free situation with the linear split-window relationship (LSWR) approach, which is based on the linear relationship exhibited between the total atmospheric water vapor and the difference of brightness temperatures $\Delta T = T_4 - T_5$ [4]–[8].

II. LASTR Method

Starting from the radiative transfer equation, for a cloud-free situation, and considering the emissivity as being equal to one for a blackbody, the transmittance through the atmosphere from the surface to the satellite in Channel i can be obtained following [9, Eq. (20)], as:

$$\tau_i = \frac{T_i - T_{ai}}{\text{SST} - T_{ai}} \tag{1}$$

where T_i is the brightness temperature measured at satellite level in Channel i (in our case AVHRR Channels 4 or 5), SST is the corresponding sea surface temperature at the time satellite passes and T_{ai} is the effective atmospheric temperature, that can be considered as the temperature at which radiates the whole atmosphere. To solve (1), it is necessary to know SST and T_{ai}. SST can be obtained using a split-window method. A multitude of split-window algorithms have been developed in recent years [10]. In this paper, we propose using two algorithms representative of the two tendencies which are more promising for obtaining accurate SST at global scale: The match-up pathfinder sea surface temperature (MPFSST) algorithm based on the first-guess principle [10] and the quadratic algorithm suggested 24 years ago by McMillin [11]. The MPFSST algorithm is based on the Nonlinear SST (NLSST) algorithm developed by Walton,

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The authors are with the Global Change Unit, Department of Thermodynamics, Faculty of Physics, University of Valencia, 46100 Burjassot, Spain (e-mail: sobrino@uv.es).

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formerly of NOAA/NESDIS [12], and has the following form:

$$\begin{aligned}\mathrm{SST}_{\mathrm{mpfsst}} = a + bT_4 + c(T_4 - T_5)\mathrm{SST}_{\mathrm{guess}} \\ + d(T_4 - T_5)(\sec(\theta) - 1) \quad (2)\end{aligned}$$

where $\mathrm{SST}_{\mathrm{mpfsst}}$ is the satellite-derived SST estimate, T_4 and T_5 are brightness temperatures in AVHRR Channels 4 and 5, respectively, $\mathrm{SST}_{\mathrm{guess}}$ is a first-guess SST value, and θ is the satellite zenith angle. Coefficients a, b, c, and d are estimated from regression analyzes using co-located *in-situ* and satellite measurements (or "matchups") on a monthly basis, and for two separate atmospheric regimes (dry and medium to moist atmospheres). This produces a statistical algorithm, tuned to bulk SST measurements. Typically, NOAA produced a set of coefficients using matchups for a certain period; these coefficients would not be modified until there was a perceived need (i.e., after the eruption of the Mt. Pinatubo volcano in June 1991, or when a new AVHRR was launched).

Moreover, in the case in which we do not have satellite zenith angle and/or $\mathrm{SST}_{\mathrm{guess}}$, the SST can be obtained from a quadratic algorithm. In this case we have used the algorithm given by [13, Eq. 3], assuming the emissivity to be equal to one for a blackbody. The MODTRAN 3.5 atmospheric transmittance radiance code was used to obtain the effective atmospheric temperature and the total water vapor content and to predict radiances for Channels 4 and 5 of NOAA-14 AVHRR with the appropriate channel filter functions. The simulations were made for a set of 60 radiosounding obtained over the sea which cover the variability of sea surface temperature (SST) (from 273 K to 330 K) and atmospheric moisture conditions (from 0.15 g cm^{-2} to 6.71 g cm^{-2}) on a world-wide scale. To obtain this variability the radiosoundings were extracted from the TOVS initial guess retrieval (TIGR) [14], [15]. The calculations included five observation angles (0°, 11.1°, 24.5°, 32.3°, and 42°), one surface temperature T_0 (T_0 is the first boundary layer temperature of the atmosphere assumed to be equal to the sea surface temperature for an atmosphere in thermodynamic equilibrium), and the emissivity equal to one for a blackbody.

As it has been explained previously, to solve (1), it is necessary to know SST and T_{ai}. To obtain the effective atmospheric temperature we have investigated the correlation between T_{ai} and SST. Fig. 1 shows the linear fit between $T_{ai(i=4)}$ and SST for AVHRR Channel 4 (the most transparent channel) with a correlation coefficient of 0.95, a bias of 0 K and a standard error of the estimate of 2.3 K. The relationship can be expressed by

$$T_{a4} = 0.9466\ \mathrm{SST} + 6.77. \quad (3)$$

A similar equation, for five LOWTRAN 7 atmospheric models, is given by [14, Eq. (8) and Fig. 2] demonstrating a basic linear relationship between model surface air temperature and mean model atmospheric temperature. To estimate W_{path}, i.e., the total water vapor content of the atmosphere along the path, a simple linear relationship between W_{path} and the atmospheric transmittance in Channel 4 is considered (see Fig. 2). The linear fit proposed from the aforementioned simulated data can be expressed by (4) with a correlation coefficient of 0.99 and standard error of the estimate of 0.2 g cm^{-2}

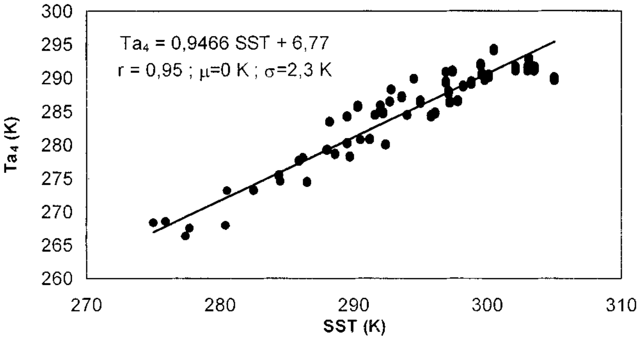

Fig. 1. Plot of simulated T_{a4} (K) at AVHRR channels four versus SST (K).

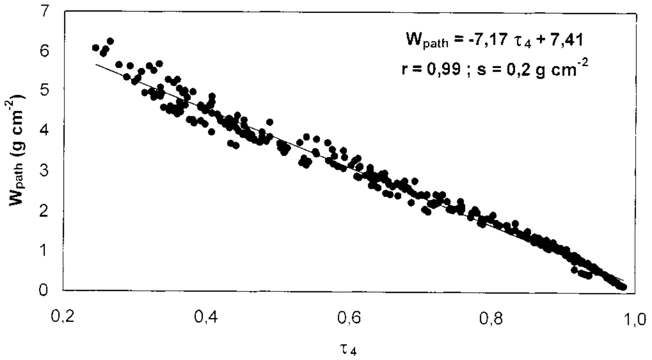

Fig. 2. Plot of simulated water vapor content along the path W_{path} (g cm^{-2}) versus simulated channel four transmissivity τ_4.

$$W_{\mathrm{path}} = -7.17\tau_4 + 7.41. \quad (4)$$

Now, we present a sensitivity analysis in order to ascertain how uncertainty in some of the values of the parameters affects the retrieved water vapor amount. A simple error analysis based on formula (4) and (1) yields

$$\delta_W \approx 0.7\delta_{T4} + 0.07(\mathrm{SST} - T_4)\delta_{Ta4} + 0.07(T_4 - T_{a4})\delta_{\mathrm{SST}}. \quad (5)$$

The error estimations was done by assuming that SST $- Ta_4 \approx$ 10 K (see Fig. 1). The errors considered are 0.1 K for the noise temperature of the AVHRR Channel 4, δ_{T4}, 2.3 K for δ_{Ta4} (according to Fig. 1), and we assumed that the error made in the determination of the SST by using the MPFSST method is about 0.6 K [12]. Finally, to evaluate (5), we used two sets of typical temperature differences values, for a dry atmosphere; $(\mathrm{SST} - T_4) = 1$ K, $(T_4 - T_{a4}) = 9$ K, and for a wet atmosphere; $(\mathrm{SST} - T_4) = 4$ K, $(T_4 - T_{a4}) = 6$ K. Thus, according to (5) we have that the error associated with the water vapor columns determination using the LASTR method varies between 0.6 g cm^{-2} to 1 g cm^{-2} approximately.

Fig. 3 summarizes the main steps in the application of the LASTR method for the calculation of the water vapor content from AVHRR Channels 4 and 5.

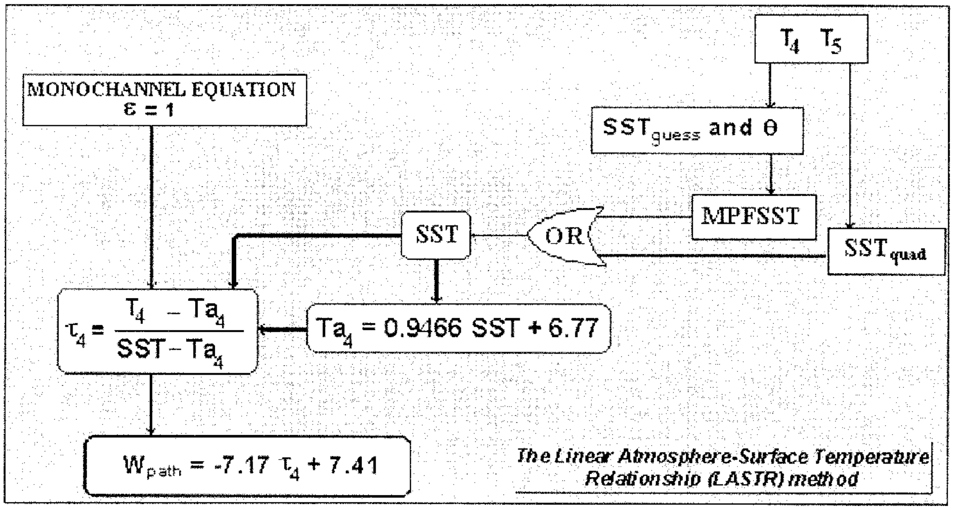

Fig. 3. Flowchart showing the main steps in the application of the linear atmosphere–surface temperature relationship method.

III. RESULTS

This section gives the results with the corresponding description of the data set (AVISO and PODAAC) used to analyze and compare, the LASTR, and LSWR methods.

A. *AVISO Data*

The AVISO database (Archivage, Visualization, Interprétation, des données des Satellites Océanographiques) is provided by Météo France for the same days as the AVHRR images [4]. Geopotential, air temperature, and relative humidity are provided at 14 pressure levels, equivalent to approximately the first 16 km of the atmosphere. The total water vapor W is obtained at each node by summating the water vapor density at each level from the initial altitude to the altitude corresponding at 100 hPa. The data have a spatial resolution of 0.5 ° and a temporal sampling of four time a day (0000 AM, 0600 AM, 0000 PM, and 0600 PM). The model enables to obtain W over sea surfaces from AVISO data with a standard error of 0.3 g cm^{-2} in comparison with radiosoundings data [17]. In our case, we have used a set of 825 data over sea surfaces for the Southwest Mediterranean basin (45° N, 35° N; 10° W, 4° E).

The AVHRR images were provided by the receiving station developed at University Louis Pasteur of Strasbourg, France. The calibration of the images is achieved using the recommendations advocated by the NOAA [18], [19]. After calibration, all images were geo-referenced. Scenes of 1400 × 1000 pixels, with a pixel size of 1 km were extracted. NOAA-14 afternoon images on 9, 10, 13, 14, 17, and 19 March 1997 were selected for their clear atmospheric conditions. In any case, there are still some pixels contaminated by clouds. Cloud detection was performed with a threshold method based on the algorithm proposed by [20].

In Table I, we present the results of the comparison between the water vapor nadir obtained from AVHRR data using (1), (4) and (3) (in [13]) [hereafter, W_{LASTR}(quad)] and that obtained from AVISO data (hereafter, W_{AVISO}) for each one of the six days considered and for all data. It should be noticed that due to the spatial resolution of the AVISO database (0.5 °), the W_{LASTR}(quad) was obtained from the averaging values on boxes of 51 × 51 pixels centered in the AVISO nodes. Moreover, the comparison has been made only for boxes in which more than 50% of pixels are cloud free. Table I shows promising results with a mean difference of about 0.5 g cm^{-2} and a standard deviation of 0.3 g cm^{-2} for all the 825 data.

TABLE I

MINIMUM (min), MAXIMUM (max), MEAN (μ), STANDARD DEVIATION (σ), ROOT, MEAN, SQUARE DEVIATION (rmsd) AND NUMBER OF DATA (N° DATA) OF THE DIFFERENCE BETWEEN W_{LASTR}(quad) OBTAINED FROM THE NOAA-14 AFTERNOON PASSES AND W_{AVISO} OVER SEA SURFACES FOR DAYS 9, 10, 13, 14, 17, AND 19 MARCH 1997. THE RESULT FOR ALL THE 825 DATA CORRESPONDING TO THE SUBSET OF THE SIX DAYS IS ALSO INCLUDED

	W_{LASTR}(quad)- W_{AVISO} (g cm^{-2})					
Day	**min**	**max**	**μ**	**σ**	**rmsd***	**N° data**
9	0.02	1.12	0.40	0.19	0.44	141
10	0.01	1.00	0.61	0.20	0.65	182
13	-0.08	1.37	0.65	0.35	0.74	175
14	-0.40	1.13	0.57	0.33	0.66	106
17	-0.05	0.76	0.29	0.18	0.34	96
19	0.08	1.24	0.62	0.24	0.66	125
six days	-0.40	1.37	0.54	0.29	0.61	825

*$\mathrm{rmsd}^2=(\mu^2+\sigma^2)$

B. *PODAAC Data*

The AVHRR pathfinder oceans match-up database (PFMDB) was obtained from the NASA Physical Oceanography Distributed Active Archive Center (PODAAC) at the Jet Propulsion Laboratory (JPL), California Institute of Technology. The Pathfinder program was jointly developed by NASA and NOAA with the goal of providing long-term, consistently calibrated global change-related data sets to Earth scientists. PFMDB is a compilation of multiyear, multisatellite data

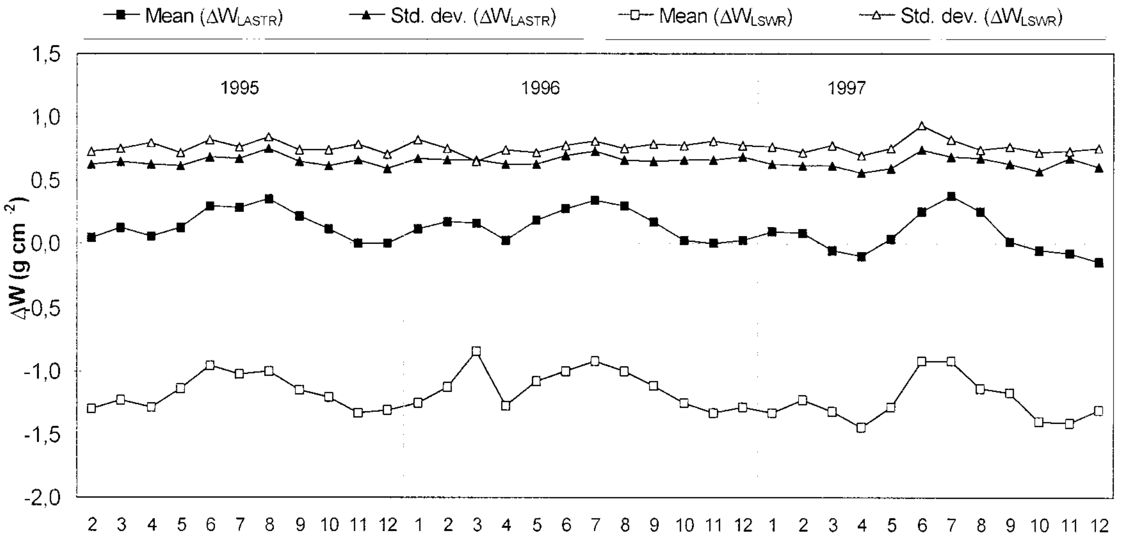

Fig. 4. Mean and standard deviation of the difference between the water vapor content at nadir given in the PODAAC database (W_{SSMI}) and the obtained applying; 1) the LASTR method for nadir view ($\Delta W_{\mathrm{LASTR}}$) and 2) the LSWR method (ΔW_{LSWR}).

of approximately cotemporal (limited to 30 min), colocated (limited to 10 km) *in-situ* sea surface temperature and AVHRR measurements. The AVHRR data are provided by the Global Area Coverage (GAC) data stream. The last step in the compilation of the PFMDB is the addition of ancillary data to the matchups, (i.e., Basin codes, etc.). A detailed description of the fields and the quality control tests are included in the AVHRR Oceans PFMDB Version 19 [21]. We have used a set of 23 788 data corresponding to all the months of the years of 1995, 1996, and 1997. These are the data that pass the filtering tests: 1) absence of sun glint, 2) absence of sun side, and 3) cloud tests. The data sets include W obtained from the SSM/I radiometer on board spacecraft of the Defense Meteorological Satellite Program (DMSP) series [22]. The W values were extracted from a set of geophysical files produced by [2] with a root, mean, square accuracy of 0.12 g cm^{-2} and a bias of 0.06 g cm^{-2} in comparison with radisoundings data. We have also used the central value in 5 × 5 extraction box for AVHRR Channels 4 and 5 and the SST obtained from the MPFSST algorithm calculated using coefficients developed for Version 4 of the pathfinder global SST fields [21]. Note, however, that this value was computed using the *in-situ* buoy temperature as the first-guess SST required by the MPFSST algorithm.

In the following, we will show the results of the comparative study we have carried out between the proposed LASTR method and the LSWR method. We notice that at this stage, for the LSWR method the coefficients of the linear fit have been obtained using the same simulated data as for the LASTR (see section A). This is important to achieve a better comparison between both methods. Thus, we have obtained: W_{nadir} (g cm^{-2}) $= 1.664(T_4 - T_5) + 0.77$ with a correlation coefficient of 0.89 and a standard error of the estimate of 0.6 g cm^{-2}.

Fig. 4 shows the mean and the standard deviation of the difference between the water vapor content nadir using the SSM/I algorithm (W_{SSMI}) given in the PODAAC database and that obtained applying; 1) the LASTR method for nadir view using (1), (3), and (4) with the SST$_{\mathrm{mpfsst}}$ given in the PODAAC database (hereafter $\Delta W_{\mathrm{LASTR}}$) and 2) the LSWR method using the given fit (hereafter ΔW_{LSWR}). The differences are made on a monthly basis (from 1 January until 12 December) for the three years of data (1995, 1996, and 1997), and for the whole of 23 788 data corresponding to all the basins. The results in Fig. 4 show a constant variation of the standard deviation for the LASTR method during the study period with a value of about 0.6 g cm^{-2}. The LSWR method shows similar behavior with a higher standard deviation value of 0.8 g cm^{-2}. For the mean value of the differences, cyclic behavior is shown for both methods. These differences are important, showing a bias of about 0.13 g cm^{-2} for the LASTR method and greater than -1 g cm^{-2} for the LSWR method. The above results show that the LASTR method provides better results than the LSWR method and therefore it is the method that we propose to obtain W from AVHRR data over sea surfaces.

Finally, it should be no that the above performance has been made comparing the LASTR estimations of W with the SSM/I retrievals which we take as "truth," and no statement is made about the effects of precipitation contamination in the SSM/I retrievals nor the spatial resolution differences with AVHRR data. In the near future it will be necessary to have access to a big database of coincident radisosounding and satellite data that permits comparing the W obtained from the LASTR method with the given by radiosounding in the different oceans.

IV. Summary and Conclusions

In this paper, we have developed a simple technique called LASTR for evaluating W from AVHRR data over sea surfaces. The LASTR method is based on a linear relationship between the effective atmospheric temperature in AVHRR Channel 4 and the surface temperature. To analyze the technique, a database of simulated data (MODTRAN 3.5), AVHRR, PODAAC, and AVISO data were used. The results indicate that the LASTR is capable of estimating W from NOAA-14 afternoon passes with a bias accuracy within 0.5 g cm^{-2} and a standard deviation of 0.3 g cm^{-2} in comparison with the W obtained by the AVISO database, while a global bias accuracy of 0.1 g cm^{-2} and a standard deviation of 0.6 g cm^{-2} have been obtained in comparison with the W included in the PODAAC database, derived from the SSM/I instrument on board spacecraft of the DMSP series.

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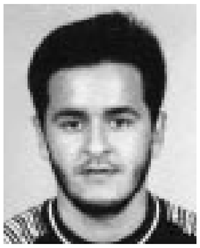
J. A. Sobrino received the B.S., M.S., and Ph.D. degrees in physics from the University of Valencia, Burjassot, Spain, in 1985, 1986, and 1989, respectively.

He has been a Professor of physics and remote sensing at the University of Valencia since 1994. He is also heading the Global Change Unit in the Department of Thermodynamics and Principal Investigator of the WATERMED project. His research interests include atmospheric correction in visible and infrared domains, the retrieval of emissivity and surface temperature from satellite image, and the development of remote sensing methods for land cover dynamic monitoring.

J. C. Jimenez received the B.S. degree in physics from the University of Valencia (UV), Burjassot, Spain, in 2000.

He is currentlly a Global Change Unit Member in the Department of Thermodynamics, UV. He works on the DAISEX project, which is carried out by ESA, obtaining surface temperature, surface emissivity, evapotranspiration, and other geobiophysical parameters from DAIS data.



N. Raissouni received the degree in applied physics from the University AbdelMaleek Essaâdi, Tétouan, Morocco in 1995 and the M.S. and Ph.D. degrees from the University of Valencia (UV), Burjassot, Spain, in 1997 and 1999, respectively.

He is currently a Global Change Unit Member, UV. His present investigations include atmospheric and emissivity correction of thermal infrared satellite imagery of the earth's surface and the development of remote sensing methods for land cove dynamic monitoring.

G. Soria received the B.S. degree in physics from the University of Valencia (UV), Burjassot, Spain, in 2000.

He is currently a Global Change Unit Member in the Department of Thermodynamics, UV. His present investigation includes the retrieval of surface temperature, including land, ice, and sea through operative and accurate multichannel and multiangle algorithms from data supplied by ATSR-1, ATSR-2, and ENVISAT-AATSR sensors.