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Physical Retrieval of Sea Surface Temperature with SEVIRI Infrared Measurements: Application to the Mediterranean in the Period 2013-2019

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Abstract. In this work, we show the results of one of the very few physical-based approaches for the estimation of surface parameters from infrared instruments on board geostationary platforms. The approach has been developed for the infrared channels of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the Meteosat Second Generation (MSG) geostationary platform and here has been applied to the region encompassing the Mediterranean, observed by more than 170000 SEVIRI pixels every 15 minutes, for the physical retrieval of the Sea Surface Temperature (SST). The methodology is based on a Kalman filter and enables simultaneous retrieval of surface emissivity and temperature from SEVIRI infrared radiance measurements using channels at 8.7, 10.8, and 12 μm. When run on a PC with a CPU clocked at 2.7GHz and 8GB of RAM, the processor needs about 0.002 s for each pixel to retrieve SST. So for the Mediterranean region, it takes about 7 minutes with a single CPU, i.e. this processor is ready for real-time computing for this region. We tested the processor by comparing its results with SST retrieved from the Advanced Very High Resolution Radiometer (AVHRR) satellite measurements. AVHRR and SEVIRI L2 SST show an excellent agreement with correlation coefficients larger than 0.99, with no bias and a root mean squared difference of less than 0.2 °C. Finally, this methodology shows that the Mediterranean Sea has warmed by four cents of Celsius per year in the last decade.

INTRODUCTION

The Mediterranean is the Sea in the "middle of the Earth" around which all the ancient western civilizations were born and where about half a billion people live. It is the largest and deepest enclosed sea on Earth with limited water exchange, high temperatures, different salinities, and high anthropologically induced pressures, including climate change. For these reasons, it is indicated as one of the potentially most vulnerable regions to the effects of Sea-level rise due to climate change [1]. Sea Surface Temperature (SST) is a key parameter to monitor climate and meteorological changes which, thanks to the increasing instruments quality, methods improvements, and spatial-temporal coverage, can be measured from space using satellite measurements with increasing accuracy. Because of its high spatial resolution (3x3 km), repeat time (15'), and the very long period of activity (2003-now), SEVIRI (Spinning Enhanced Visible and Infrared Imager) on board of MSG (Meteosat Second Generation) geostationary platform, provides very useful measurements for the estimation of SST parameter. To fully take advantage of the data information content, we developed a Kalman filter methodology for the simultaneous retrieval of surface emissivity and temperature from SEVIRI infrared radiance measurements using channels at 8.7, 9.7, 10.8, and 12 μm [2]. Unlike most of the techniques used for SST retrieval [3, 4], the one developed is one of the very few physical-based approaches for the estimation of surface parameters from infrared instruments onboard geostationary platforms and, compared with other satellite retrievals, analyses, and ground-based measurements, it has shown an accuracy of ± 0.005 and ± 0.2 K, for surface emissivity and temperature respectively [5]. Based on this Kalman filter methodology a Level 2 (L2) processor has been developed to provide surface emissivity and temperature in real-time, making it very attractive for application in different fields. In this work, we have applied this L2 processor for the retrieval of the Mediterranean SST for the period 2013-2019. This article is organized as follows: the next session briefly describes the data and methods used, providing more references for further information. Then the main results will be described and finally, some conclusions will be drawn.

DATA AND METHOD

This section describes SEVIRI data first and then both the forward and inverse model we developed for SEVIRI.

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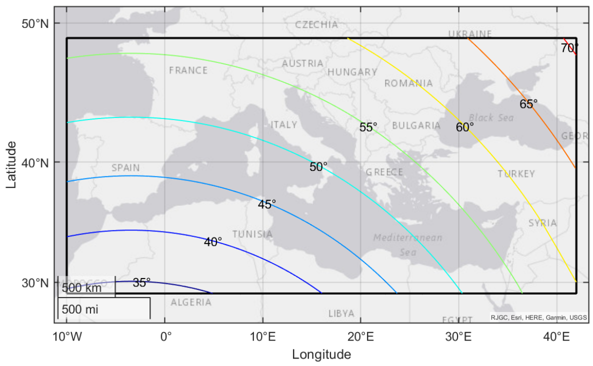

FIGURE 1: The region investigated in this work. Colored contour lines in the figure indicated SEVIRI Vertical Zenith Angle.

TABLE 1: Central position of SEVIRI infrared channels both in wavelength and wavenumber, and its Noise Equivalent Difference Temperature (NEDT).

ch. #	wavelength center, μm	wavenumber center, cm^{-1}	NEDT, K
4	3.9	2564	0.35 @ 300 K
5	6.2	1613	0.75 @ 250 K
6	7.3	1370	0.75 @ 250 K
7	8.7	1148	0.28 @ 300 K
8	9.7	1035	1.5 @ 255 K
9	10.8	929	0.25 @ 300 K
10	12.0	838	0.37 @ 300 K
11	13.4	746	1.80 @ 270 K

Data. SEVIRI provides every 15 minutes image data in eight thermal infrared channels listed in Tab. 1. Our methodology [2, 5, 6] has been specifically developed, optimized, and tested for the three atmospheric window infrared channels: Channels 7, 9, and 10 respectively centered at 8.7, 10.8, and 12 μm, which are the channels for which we can retrieve emissivity. SEVIRI spectral radiances have been acquired in the period between 2013-2019 for the Mediterranean region i.e. the target area shown (black box) in Fig. 1. The area, bounded in longitude between 10°W and 42°E and in latitude between 29°N and 49°N, contains 640379 SEVIRI pixels with a vertical zenith angle between 33.8° and 70.3°. Among these pixels 233015 are over the sea with a Vertical Zenith Angle between 35.3° and 68.0° covering the whole Mediterranean Sea (171852 pixels, with a VZA in the range between 40.5° and 59.5°), the Black Sea (21337 pixels) and a part of Easter Atlantic Ocean (38397 pixels). We also acquired the operational cloud masks released by EUMETSAT for the MSG platform in order to filter out cloudy pixels from the retrieval chain.

The forward model: $\sigma-$SEVIRI. The forward model calculates the SEVIRI radiance spectrum, which is then used in the retrieval scheme. Our forward model is called σ-SEVIRI and it is fully described in [7]. The methodology in our forward model is based on the one we developed for the hyperspectral sensors like IASI [8], i.e. σ-IASI [9, 10, 11]. The model has been used and evaluated with both upwelling and downwelling spectral radiances in the range 100 to 3000 cm^{-1} (e.g., see [12, 13, 14, 15, 16, 17]). σ-IASI is a pseudo-monochromatic radiative transfer model that takes into account both Specular and Lambertian reflection. The code is based on an optical depths look-up table and an interpolations procedure. With SEVIRI spectral resolution it is possible to strongly reduce the dimensionality of the data space based on the assumption that any given SEVIRI radiance can be represented as a function of only a few monochromatic quantities or predictors. This way, we can save storage and computational time making this methodology ready for real-time applications [7].

The retrieval scheme: $\delta-$SEVIRI. The methodology we developed is one of the very few physical-based approaches for the estimation of surface parameters from infrared instruments on board geostationary platforms and it has shown [2, 5, 6, 7] an accuracy of ±0.005 and ±0.2 K, for surface emissivity and temperature respectively, when its results are compared with ground-based measurements and satellite products. The results of this L2 Processor are a pre-operational product of Land Satellite Facility of EUMETSAT (LSA SAF, https://landsaf.ipma.pt). The products are available at link https://landsaf.ipma.pt/en/products/land-surface-temperature/memd/. Emissivity and surface temperature are simultaneously retrieved with a Kalman filter approach. Even if the scheme could be applied to the $m = 8$ infrared channels of the SEVIRI imager listed in Tab. 1, the Level 2 processor uses the retrieved state vector of m=3 SEVIRI infrared channel emissivities and surface temperature (channels 7, 9 and 10). It is important to stress that in the current case since we dealt only with SEVIRI pixels over the sea, we retrieved the T_s alone, whereas for sea surface emissivity is defined and derived according to Masuda's emissivity model [18]. To take into account the atmosphere absorption/emission, ECMWF (European Centre for Medium-range Weather Forecasts) operational analysis provides the state vector (Temperature, Water Vapour, and Ozone profiles). To compensate for the different spatial and temporal resolutions, the ECMWF analysis was linearly interpolated over time and to the nearest point in space. The procedure takes less than 10 minutes when run on 20 CPUs to retrieve surface emissivity and temperature for a single acquisition of the entire SEVIRI disk, even assuming all pixels are under clear sky conditions. A single SEVIRI acquisition for a limited region, such as the Mediterranean area, is processed in 7 minutes with a single CPU making the procedure ready for real-time application.

TABLE 2: Time series model of Eq. 1: fitted parameters and their 95% confidence interval for the Mediterranean.

Coefficients	m	T_0	$T_{1/2}$	T_1	T_2	$\varphi_{1/2}$	φ_1	φ_2
Units	°C/Year	°C	°C	°C	°C	rad	rad	rad
Value	0.04	20.3	0.1	5.7	0.6	-1.3	-2.69	-0-08
95% Confidence Interval	(0.0, 0.09)	(20.1, 20.5)	(0.0, 0.3)	(5.6, 5.9)	(0.5, 0.7)	(-2.3, -0.3)	(-2.71, -2.66)	(-0.28, 0.12)

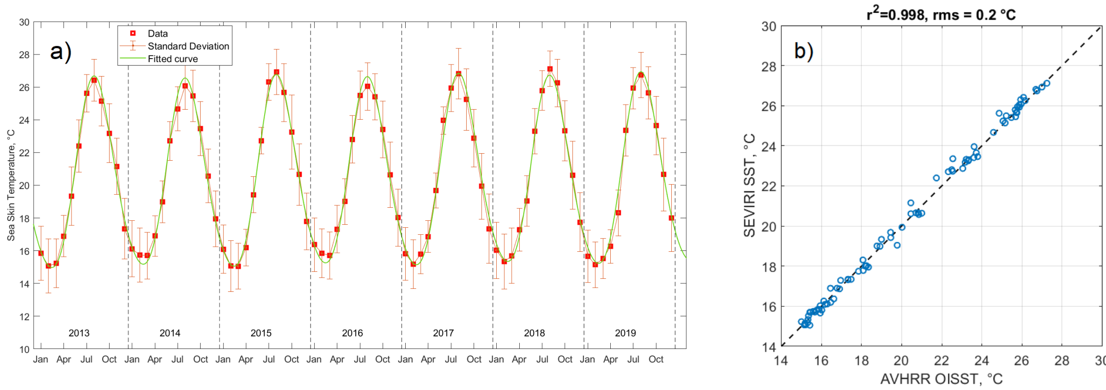

FIGURE 2: Panel a) shows the retrieved SST monthly mean and standard deviation (in red) and harmonic fit (green line). Panel b) shows the scatter plot of SST derived from SEVIRI with respect to the ones derived from AVHRR.

RESULTS

At the website http://www2.unibas.it/gmasiello/assite/as/products.html, the monthly mean SST for the whole dataset is freely available. Here for sake of brevity, to extract quantitatively annual cycle and seasonal trends, we have fitted the monthly mean retrieved temperature for the Mediterranean sea time series using Fourier expansions truncated to the first two harmonics and a biannual harmonics term with a linear trend term,

$$T_s(t) = T_0 + mt + T_{1/2}\sin\left(\frac{\pi t}{T} + \varphi_{1/2}\right) + T_1\sin\left(\frac{2\pi t}{T} + \varphi_1\right) + T_2\sin\left(\frac{4\pi t}{T} + \varphi_2\right) \tag{1}$$

where t is the time running over the months (1 = January 2013,...,84 = December 2019), $T = 12$ months is the basic period and $T_s(t)$ stands for retrieval. In Fig. 2 a) red dots and red bar are respectively the monthly mean and standard deviation of the Mediterranean SST, while the green line is the fit described by Eq. 1 with retrieved parameters in Table 2. The fit of Eq. 1 to the SEVIRI retrieved SST data shows a determination coefficient of $r^2 = 0.990$ and *rmse* (root mean square error) of 0.3°C. The fitted coefficients (T_0, m, $T_{1/2}$, $\varphi_{1/2}$, T_1, φ_1, T_2 and φ_2) are shown in Table 2. From this table, we see that the Mediterranean Sea shows an increasing trend (coefficient m) of 0.04°C/Year. For the same period, similar values of a warming trend and monthly Temperatures were obtained using Optimal Interpolation SST retrieved from the Advanced Very High Resolution Radiometer (AVHRR) [19]. Fig. 2 b) shows the scatter plot of SST derived from SEVIRI with respect to the ones derived from AVHRR. The two series are in excellent agreement showing a determination coefficient of 0.998 and a root mean square difference of 0.2°C.

CONCLUSION

We developed a Kalman filter methodology for the physical retrieval of Surface Temperature and Emissivity from SEVIRI radiances at the full spatial (3x3 km) and temporal resolution (15 minutes). The algorithm can be specialized for land or sea or both. The methodology is ready for real-time application to SEVIRI full disk using 20 CPUs. An application for the Mediterranean basin has been developed, which can run in real-time also on one single CPU. The retrieved emissivity is a pre-operational product of LSA-SAF. With this L2 processor, we retrieved the Mediterranean

Sea surface temperature for the period 2013-2019 for which we found that the Mediterranean Sea is warming up at a rate of 0.04°C/Year. This result is in excellent agreement with AVHRR OI-SST products. We plan to extend our analysis to all SEVIRI data in order to cover the period 2003-present.

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SEVIRI radiance and MSG cloud masks have been downloaded from the EUMETSAT Earth Observation portal (https://archive.eumetsat.int/usc/UserServicesClient.html). Access to the ECMWF database was obtained with ECMWF Meteorological Archival and Retrieval System (MARS).

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