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Use of external solar spectra to multispectral sensor systems as an alternative for radiometric correction and calibration of ToA reflectance

Uso de espectros solares externos aos sistemas de sensores multiespectrais como alternativa para a correção e calibração radiométrica da reflectância ToA

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Abstract

Most Earth observation satellite missions do not have instruments to measure solar irradiance in orbit. Consequently, the temporal variability of the recorded reflectance is based only on the radiance measured by the sensor, since the incident solar irradiance is considered constant. This approach neglects non-seasonal variability associated with solar activity and can compromise the accuracy of reflectance values. The aim of this study was to investigate if solar spectra obtained daily by instruments external to multispectral sensor systems can contribute to increasing the accuracy of top-of-atmosphere (ToA) reflectance data. Solar spectra from the Spectral Irradiance Monitor (SIM/SORCE) instrument and ToA reflectance data from the Enhanced Thematic Mapper Plus (ETM+/Landsat-7) sensor were used. ToA reflectance data from the Radiometric Calibration Network portal was used as a reference for the accuracy analysis. The results indicate that the use of SIM/SORCE solar spectra in the radiometric correction of ETM+/Landsat-7 ToA reflectance can help increase the accuracy rates of ToA reflectance in the green (> ∼1%), red (> ∼0.1%), NIR (> ∼0.1%), SWIR-1 (> ∼3%) and SWIR-2 (> ∼2%) spectral bands. In addition, contributions to temporal stability were found in the blue, green, NIR and SWIR-1 bands (< ∼0.2%). We conclude that the use of external daily solar spectra can contribute to improving the accuracy and temporal stability of ToA reflectance values obtained by multispectral sensor systems whose pre-processing is based on radiance values.

Keywords:

Eleven-year solar cycles, Spectral Irradiance Monitor, Enhanced Thematic Mapper Plus, Radiometric Calibration Network, Accuracy.

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Resumo

A maioria das missões de satélite de observação da Terra não possui instrumentos para medir a irradiância solar em órbita. Por consequência, a variabilidade temporal da reflectância registrada é baseada apenas na radiância medida pelo sensor, uma vez que a irradiância solar incidente é considerada constante. Tal abordagem negligencia variabilidades não sazonais associadas às atividades solares e pode comprometer a acurácia dos valores de reflectância. O objetivo deste estudo foi investigar se espectros solares obtidos diariamente por instrumentos externos a sistemas de sensores multiespectrais podem contribuir para o aumento da acuracidade dos dados de reflectância do topo da atmosfera (ToA). Foram utilizados espectros solares do instrumento Spectral Irradiance Monitor (SIM/SORCE) e dados de reflectância ToA do sensor Enhanced Thematic Mapper Plus (ETM+/Landsat-7). Os dados de reflectância ToA do portal Radiometric Calibration Network foram utilizados como referência para a análise de acurácia. Os resultados indicam que o uso dos espectros solares do SIM/SORCE na correção radiométrica da reflectância ToA do ETM+/Landsat-7 possibilita contribuir para aumentar as taxas de acuracidade da reflectância ToA nas bandas espectrais do verde (> ~1%), vermelho (> ~0,1%), NIR (> ~0,1%), SWIR-1 (> ~3%) e SWIR-2 (> ~2%). Além disso, foram constatadas contribuições para a estabilidade temporal nas bandas do azul, verde, NIR e SWIR-1 (< ~0.2%). Concluímos que o uso de espectros solares diários externos pode contribuir para o melhoramento da acurácia e da estabilidade temporal dos valores de reflectância ToA obtidos por sistemas de sensores multiespectrais cujo pré-processamento é baseado em valores de radiância.

Palavras-chave:
Ciclos solares de onze anos, Spectral Irradiance Monitor, Enhanced Thematic Mapper Plus, Radiometric Calibration Network, Acurácia.

I. INTRODUCTION

The accuracy of the top-of-atmosphere (ToA) reflectance values obtained by multispectral remote sensing (RS) systems is fundamental to promote the reliability and credibility of the results obtained through studies based on the use of these products (Helder et al., 2010; Müller; Vibrans, 2024). The practices currently implemented for processing these data make it possible to obtain a high level of assertiveness (>95%) (Markham et al., 2014; USGS, 2019a; USGS, 2019b). However, the constant improvement of these methodologies is essential to ensure the quality of the data obtained, as well as the research carried out using this information.

In this context, the accuracy improvement of RS data tends to be the result of the sum of small specific contributions that can affect the following image processing stages (Müller; Vibrans, 2024). It is well known that 11-year solar cycles (long term) and short-term solar activity phenomena interfere with the energy balance incident on the ToA. Thus, RS systems whose radiometric correction is based on radiance values (when only the variability of the signal recorded by the sensor is taken into account while the solar irradiance is assumed to be constant) may compromise the accuracy of the ToA reflectance values (Müller; Vibrans; Pinto, 2024; Müller;

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Vibrans, 2024). In these cases, where sensor systems do not have instruments for directly measuring solar spectral irradiance in orbit, the mean exoatmospheric solar irradiance (ESUN) parameter is standardized to a fixed value during preprocessing of the collected data (Markham et al., 2002; Li et al., 2020; Müller; Vibrans; Pinto, 2024; Müller; Vibrans, 2024). This fixed value is used during the entire sensor's operating period.

Some of the more recent RS systems, such as OLI/Landsat-8 and OLI-2/Landsat-9, have integrated instruments that collect and intermittently record solar irradiance data in orbit to support radiometric calibration and minimize the effects of non-seasonal variability in incident energy (Thome, 2001; Markham et al., 2014; USGS, 2019b). In these cases, radiometric calibration and correction are based on reflectance values (Markham et al., 2014; THOME, 2001). However, sensor systems that do not have this capability (which represents most Earth observation satellite missions), which are responsible for obtaining the historical collection of information about the Earth's surface, may impair the temporal stability of the recorded data impaired (Müller; Vibrans; Pinto, 2024; Müller; Vibrans, 2024). Consequently, temporal monitoring studies of land use and occupation, as well as studies that estimate biophysical variables such as plant biomass and water quality, can record small variations that do not come from the observed targets, but from incident solar irradiance that was not properly corrected during data preprocessing (Müller; Vibrans; Pinto, 2024; Müller; Vibrans, 2024).

In this context, the aim of this study is to investigate whether solar spectra obtained daily by instruments external to multispectral sensor systems, whose radiometric calibration is based on radiance, can improve the accuracy of the preprocessing of ToA reflectance data from various sensors. The study has three specific objectives: (i) to evaluate the contribution of the solar spectra of the SIM/SORCE instrument to the radiometric correction and calibration of the ToA reflectance of the ETM+/Landsat-7 sensor and, consequently, of multispectral sensors whose pre-processing is based on radiance values; (ii) analyze the impact of using SIM/SORCE daily solar spectra on recovering the effects caused by solar activities on the temporal stability of the ETM+/Landsat-7 ToA reflectance values; and (iii) obtain theoretical insights to illustrate the use of daily solar spectra external to the satellite mission used for the correction and radiometric calibration of the ToA reflectance of its data. We hope that using external daily solar spectra for the radiometric correction and calibration of multispectral sensor ToA reflectance will enhance the accuracy and temporal stability of these data.

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II. Materials and Methods

The methodology of this study (represented by a graphic summary in the supplementary materials file) involves the analysis and comparison of three sets of ToA reflectance data: one set comprising reference values provided by RadCalNet; another set corresponding to the original values obtained by the ETM+/Landsat-7 sensor; and a third set of ETM+/Landsat-7 values radiometrically corrected with the solar spectra from the SIM/SORCE instrument.

2.1 Data acquisition

2.1.1 Reference ToA reflectance data

The reference ToA reflectance values used were obtained from RadCalNet [https://www.radcalnet.org/], an initiative established in 2013 to provide data with temporal and spatial consistency for the radiometric calibration of Earth observation optical remote sensors (Bouvet et al., 2014). The network comprises four automated data collection sites: La Crau, in France; Railroad Valley Playa, in Nevada, USA; Baotou, in China; and Gobabeb, in Namibia.

RadCalNet provides ToA reflectance data obtained for nadir viewing at 30-minute intervals (from 9 a.m. to 3 p.m. standard time at each site) (Bouvet et al., 2014). The data provided covers the electromagnetic spectrum from 400 nm to 1000 nm (at all sites) and some sites provide wider spectral coverage of up to 2500 nm, with a spectral resolution of 10 nm (Bouvet et al., 2014).

Each RadCalNet site has instrumentation to collect base-of-atmosphere (BoA) reflectance data and atmospheric measurements such as aerosol spectral optical depth, aerosol size, ozone and water vapor (Bouvet et al., 2014). Atmospheric data are used to perform atmospheric correction on BoA reflectance values and thus generate ToA reflectance information using the MYSTIC radiative transfer model (Bouvet et al., 2014). The ToA reflectance, BoA reflectance and atmospheric measurements datasets for each of the sites have been available since 2018. The RadCalLNet site configurations can be found in Table 1 of the supplementary materials file. These data were utilized to derive time series of reference ToA reflectance values, calculated for different spectral bands.

2.1.2 ToA reflectance data from Enhanced Thematic Mapper Plus (ETM+)

The ETM+ sensor is a multispectral radiometer aboard the Landsat-7 satellite and produces high-resolution images of the Earth's surface in the visible (VIS), near infrared (NIR), shortwave infrared (SWIR) and thermal infrared spectral regions (USGS, 2019a). Its spatial resolution is 30 m in the VIS, NIR and SWIR bands

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(USGS, 2019a). The radiometric resolution is 8 bits and the temporal resolution is 16 days, respectively, and it has a Sun-synchronous polar orbit at an altitude of 705 km (USGS, 2019a). Radiometric calibration and correction are based on radiance values (Markham et al., 2002).

We used clippings from the ETM+/Landsat-7 (Collection-2 Level-1) scenes that coincide with the five RadCalNet data collection sites. The reflectance data from the ETM+ scene clippings (median pixel values) constitute the original ETM+ ToA reflectance time series used during the analyses.

The ETM+ sensor was selected for this study for three reasons: 1) because it coincides with the data collection period of the SIM/SORCE instrument, as described in sub-item 2.1.3; 2) to make it possible to analyze the gap indicated by Müller and Vibrans (2024) regarding improving the accuracy of radiometric correction of ToA reflectance with the help of SIM/SORCE solar spectra; and 3) to investigate the possibility of using variable solar spectra to improve the accuracy of reflectance products from satellite missions whose calibration and radiometric correction is based on radiance values (Markham et al., 2014).

2.1.3 Solar spectra data from the Spectral Irradiance Monitor (SIM)

SIM/SORCE is a spectroradiometer that collects and records daily ToA solar irradiance data in the spectral regions between 310 and 2400 nm and with a spectral resolution between 1 and 27 nm (Harder et al., 2005; LASP, 2022). The values provided are standardized for an average Earth-Sun distance of one astronomical unit (1 AU) and the relative line-of-sight velocity is zero in relation to the Sun (Harder et al., 2005; LASP, 2022). The SIM/SORCE instrument collected daily ToA solar spectral irradiance data between April 2003 and February 2020 [https://lasp.colorado.edu/home/sorce/data/].

Although there are orbital missions with more precise instruments for monitoring ToA solar irradiance, such as the Total and Spectral Solar Irradiance Sensor (TSIS-1), SIM/SORCE data was used because it coincided simultaneously with the availability of ToA reflectance data at all RadCalNet sites during the period of ETM+ operation.

The scenes/dates analyzed in this study's methodological proposal were chosen based on the simultaneous availability of ToA reflectance data from RadCalNet, ETM+ sensor scenes obtained from RadCalNet sites, and ToA solar spectral irradiance data recorded by the SIM instrument.

2.2 Data processing and analysis

2.2.1 Solar spectra data from the Spectral Irradiance Monitor (SIM)

The radiometric correction applied to the ToA reflectance values obtained from the ETM+ sensor was performed by adjusting the ESUN parameter for each of the scenes analyzed. Since this parameter is considered

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constant during the derivation of the original ToA reflectance values for the scenes, the daily solar spectra recorded by the SIM/SORCE instrument were used to calculate the adjusted ESUN values, as proposed by Müller, Vibrans and Pinto (2024) (Equation 1).

$$ESUN = \frac{\int_{\lambda_1}^{\lambda_2} E(\lambda) \cdot SRF(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} SRF(\lambda)\, d\lambda} \quad [\mathrm{Wm^{-2}}\mu\mathrm{m^{-1}}] \tag{1}$$

Where λ_1 and λ_2 are the spectral limits of the ETM+ band (*nm*); E(λ) is the spectral solar irradiance at the ToA obtained by the SIM/SORCE instrument for wavelength λ ($Wm^{-2}\mu m^{-1}$); and SRF(λ) is the spectral response value of the ETM+ band region (available at [https://landsat.usgs.gov/spectral-characteristics-viewer]) for wavelength λ (dimensionless). The integrations proposed in Equation 1 were carried out numerically using the trapezoidal method, since the ToA solar irradiance data and spectral response values are discrete. More details on this methodology can be found in the Materials and Methods section of Müller, Vibrans and Pinto (2024).

2.2.2 Calculation of ToA reflectance values

Time series were analyzed containing ToA reflectance values for the five RadCalNet operating sites (RVUS, LCFR, GONA, BTCN and BSCN) and the six ETM+ spectral bands (blue, green, red, NIR, SWIR-1 and SWIR-2). These datasets were obtained according to the availability of ToA reflectance data from the RadCalNet portal and ToA solar spectral irradiance data from the SIM/SORCE instrument, simultaneously. The calculations for obtaining the different classes of ToA reflectance values analyzed are detailed below.

2.2.2.1 Reference ToA reflectance - RadCalNet

The values that make up the reference ToA reflectance time series were obtained by integrating the data available on the RadCalNet portal for the spectral regions belonging to the analyzed bands of the ETM+/Landsat-7 sensor (Equation 2).

$$\rho_{REF} = \frac{\int_{\lambda_1}^{\lambda_2} \rho(\lambda) \cdot SRF(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} SRF(\lambda)\, d\lambda} \quad [\text{dimensionless}] \tag{2}$$

Where ρ_{REF} is the reference ToA reflectance for the spectral bands analyzed (dimensionless); λ_1 and λ_2 are the spectral limits of the ETM+ bands (*nm*); ρ(λ) is the ToA spectral reflectance provided by RadCalNet for

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wavelength λ (dimensionless); and SRF(λ) is the spectral response value of the ETM+ band regions (available at [https://landsat.usgs.gov/spectral-characteristics-viewer]) for wavelength λ (dimensionless). The integrations proposed in Equation 2 were carried out numerically using the trapezoidal method.

As a result, a time series with reference values was obtained to compare with the reflectances recorded by the ETM+/Landsat-7 for the selected targets. The spectral limits of each band analyzed were used and the values of $\rho(\lambda)$ closest to the acquisition time of the scenes from each sensor were chosen.

2.2.2.2 Original ToA reflectance - ETM+

Initially, the ETM+/Landsat-7 scenes were cropped according to the five RadCalNet data collection sites. For each subset obtained (clipper), representing surfaces with homogeneous characteristics, the median of the pixels within the subset calculated (in digital number - DN), excluding null or saturated values so that pixels impacted by noise do not compromise the analysis. The median value was used as a reference to calculate the radiance (Equation 3) and subsequently the reflectance (Equation 4) values for the ETM+ scenes.

$$L_0 = \left(\frac{L_{max}-L_{min}}{DN_{max}-DN_{min}}\right)\cdot(DN - DN_{min}) + L_{min} \qquad [Wm^{-2}\mu m^{-1}] \tag{3}$$

With L_0 representing the median value of the radiance from the ETM+ clippers ($Wm^{-2}\mu m^{-1}$); L_{max} and L_{min} representing the maximum and minimum radiance, respectively, of the ETM+ bands analyzed ($Wm^{-2}\mu m^{-1}$); DN_{max} and DN_{min} representing the maximum and minimum digital number of each band analyzed, respectively (dimensionless); and DN the digital number corresponding to the median value of each clipper (dimensionless). Details on L_{max}, L_{min}, DN_{max} and DN_{min} are provided in the metadata file of the scenes in the analyzed time series.

$$\rho_{ETM+} = \frac{\pi\, L_0\, d^2}{ESUN\,\cos(\theta_Z)} \quad [\text{dimensionless}] \tag{4}$$

Where ρ_{ETM} is the original ToA reflectance of the ETM+ clippers (dimensionless); L_0 is the corresponding ToA radiance, obtained using Equation 3 ($Wm^{-2}\mu m^{-1}sr^{-1}$); d is the Earth-Sun distance (AU); and θ_Z is the solar zenith angle (radians); and ESUN is the incident solar irradiance parameter. The d and θ_Z values for each scenes used are available in the respective scene metadata file. Standardized ESUN values were used, as suggested in the Landsat 7 handbook: 1970 $Wm^{-2}\mu m^{-1}$ for band 1 (blue); 1842 $Wm^{-2}\mu m^{-1}$ for band 2 (green); 1547 $Wm^{-2}\mu m^{-1}$ for band 3 (red); 1044 $Wm^{-2}\mu m^{-1}$ for band 4 (NIR); 225. 7 $Wm^{-2}\mu m^{-1}$ for band 5 (SWIR-1) and 82.06 $Wm^{-2}\mu m^{-1}$

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for band 7 (SWIR-2) (USGS, 2019a). These parameters were generated using the ChKur solar spectrum (USGS, 2019a).

The values obtained for ρETM+ make up the original ToA reflectance time series from the ETM+/Landsat-7 sensor. These were used to analyze the sensor's accuracy in relation to the RadCalNet reference values (reference ToA reflectance).

2.2.2.3 Corrected ToA reflectance - ETM+/SIM

The ETM+ corrected ToA reflectance values (ρ_{FIXED}) were obtained by implementing radiometric correction using adjusted variable solar spectra, as proposed by Müller, Vibrans and Pinto (2024). This step consists of correcting the ESUN values according to Equation 1 and then applying these results to the calculation of the ETM+ ToA reflectance (Equation 4), replacing the standardized ESUN with the corrected one. The results obtained make up the ETM+ corrected ToA reflectance time series and were used to quantify the accuracy of the radiometric correction based on the use of SIM/SORCE solar spectra.

For the two sets of ToA reflectance data from the ETM+ sensor (ρ_{ETM+} and ρ_{FIXED}), only the scenes without cloud cover at the analyzed locations (sites) were used, while the ToA reflectance data from RadCalNet is available with atmospheric correction to eliminate possible effects from the presence of clouds during data collection.

2.2.3 Analysis of the accuracy of ToA reflectance data

The accuracy of the original and corrected ToA reflectance values was obtained by considering the difference between the RadCalNet reference values. A direct comparison of the accuracy between the original and corrected ETM+ datasets was made using the Enhanced Accuracy Parameter (EAP) proposed for this study (Equation 5).

$$EAP = \left(\frac{|\rho_{ORI} - \rho_{REF}| - |\rho_{FIX} - \rho_{REF}|}{\rho_{REF}}\right) \cdot 100 \quad [\%] \tag{5}$$

With ρ_{ORI} and ρ_{FIX} representing the original and corrected ETM+ ToA reflectances (dimensionless), respectively; and ρ_{REF} indicating the reference ToA reflectance (dimensionless). The EAP value indicates the percentage impact on the accuracy of the ToA reflectance values in relation to the reference standard provided by RadCalNet. This can be positive, indicating an improvement in the accuracy of the corrected scenes, or

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negative, signaling a worsening. A detailed description of the EAP values obtained from each of the sites analyzed is presented in the supplementary materials file.

Other statistical metrics were used to support the analysis of the accuracy improvement of the corrected values. The following parameters were calculated: Symmetric Mean Absolute Percentage Error (SMAPE); Mean Absolute Percentage Error (MAPE); Mean Absolute Error (MAE); and BIAS.

2.2.4 Analysis of the temporal stability of ToA reflectance values

To quantify the effect that solar activity events have on the long-term temporal stability of the ToA reflectance of the analyzed scenes, the Enhanced Temporal Stability (ETS) parameter (Equation 6) was used, as proposed by Müller and Vibrans (2024).

The ETS values suggest the percentage of temporal stability that can be improved during the implementation of the proposed radiometric calibration (Müller; Vibrans, 2024). This comparison was made between the pair of ETM+ corrected ToA reflectance time series in relation to the original ETM ToA reflectance. In this approach, positive values indicate a reduction in the dispersion of the data that makes up the analyzed time series in relation to the reference series (enhanced temporal stability), while negative values indicate an increase in the dispersion of this data (less stability).

$$ETS = \left(\frac{CV_1 - CV_2}{CV_1}\right) \cdot 100 \quad [\%] \tag{6}$$

Where CV_1 e CV_2 represent the coefficients of variation (CV) of the ToA reflectance of the pair of time series compared (dimensionless), with CV_2 in relation to CV_1.

Statistical tests were also carried out to compare variances between the compared time series. Bartlett's test was used for parametric data sets and Levene's test for non-parametric data. The results of the temporal stability analysis for each of the sites are presented in the supplementary materials file.

All parameters analyzed in this study were obtained from the raw data set (with outliers). Since the effects of outliers are proportional in the two analyzed data sets (of original and corrected values), they do not hinder the comparison of accuracy and temporal stability between these values. The digital image processing and all the calculations and analyses proposed in this study were implemented in Python.

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III. RESULTS

The results obtained from the analysis of the number of scenes with improved accuracy show that the proposed correction can contribute to increasing the accuracy of the ETM+ sensor's ToA reflectance products in the red, NIR, SWIR-1 and SWIR-2 spectral bands (Table 1). However, considering that these results reflect an average of the compilation of the five sites, the isolated analysis of the results obtained for each site may provide different interpretations regarding the improvement in accuracy by spectral band (see supplementary materials). In these isolated cases, the corrected ToA reflectance of a given band may show an accuracy improvement or worsening compared to the analysis with data from all the compiled sites.

However, considering the results of the statistical error metrics (SMAPE, MAPE, MAE and BIAS), it can be seen that the corrected ETM+ ToA reflectance data showed more accurate values than the original ETM+ data in all spectral bands, except for the blue band (Table 1). However, separate analysis of the results for each site may allow different interpretations regarding the spectral regions with the best accuracy (see supplementary materials).

Table 1 – Compilation of the accuracy analysis of the original and corrected ToA reflectance values from the ETM+ sensor in relation to the reference data from the five RadCalNet sites.

Band	Data	Total Scenes	Scenes with better accuracy		SMAPE (%)	MAPE (%)	MAE	BIAS
			N	%				
Blue	ETM+	145	92	63.45	10.2846	9.9687	0.0210	0.0014
	FIXED	145	53	36.55	10.7215	10.2296	0.0216	-0.0028
Green	ETM+	142	73	51.41	10.3000	9.6411	0.0214	0.0012
	FIXED	142	69	48.59	10.3024	9.5616	0.0213	-0.0010
Red	ETM+	144	64	44.44	10.1548	9.3874	0.0226	0.0019
	FIXED	144	80	55.56	10.1545	9.3866	0.0226	0.0019
NIR	ETM+	145	48	33.10	12.2567	12.0970	0.0312	0.0142
	FIXED	145	97	66.90	12.2506	12.0899	0.0312	0.0142
SWIR-1	ETM+	113	49	43.36	9.0713	8.0214	0.0277	0.0020
	FIXED	113	64	56.64	8.7843	7.5312	0.0258	-0.0090
SWIR-2	ETM+	26	1	3.85	14.7263	13.5214	0.0247	-0.0165
	FIXED	26	25	96.15	13.3244	12.3436	0.0223	-0.0133

Source: authors.

Individual analyses of the improved temporal stability at each of the sites suggest small contributions (ETS < 0.2%) in all the spectral bands analyzed (see supplementary materials). However, the analysis of variance between the observed sets indicates that none of these changes are significant (p-value > 0.05). Further details on these results are presented in the supplementary materials. The SWIR bands have a smaller number of scenes

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analyzed due to the lower amount of RadCalNet data available for this spectral region, since only the La Crau site has instruments that operate at these wavelengths.

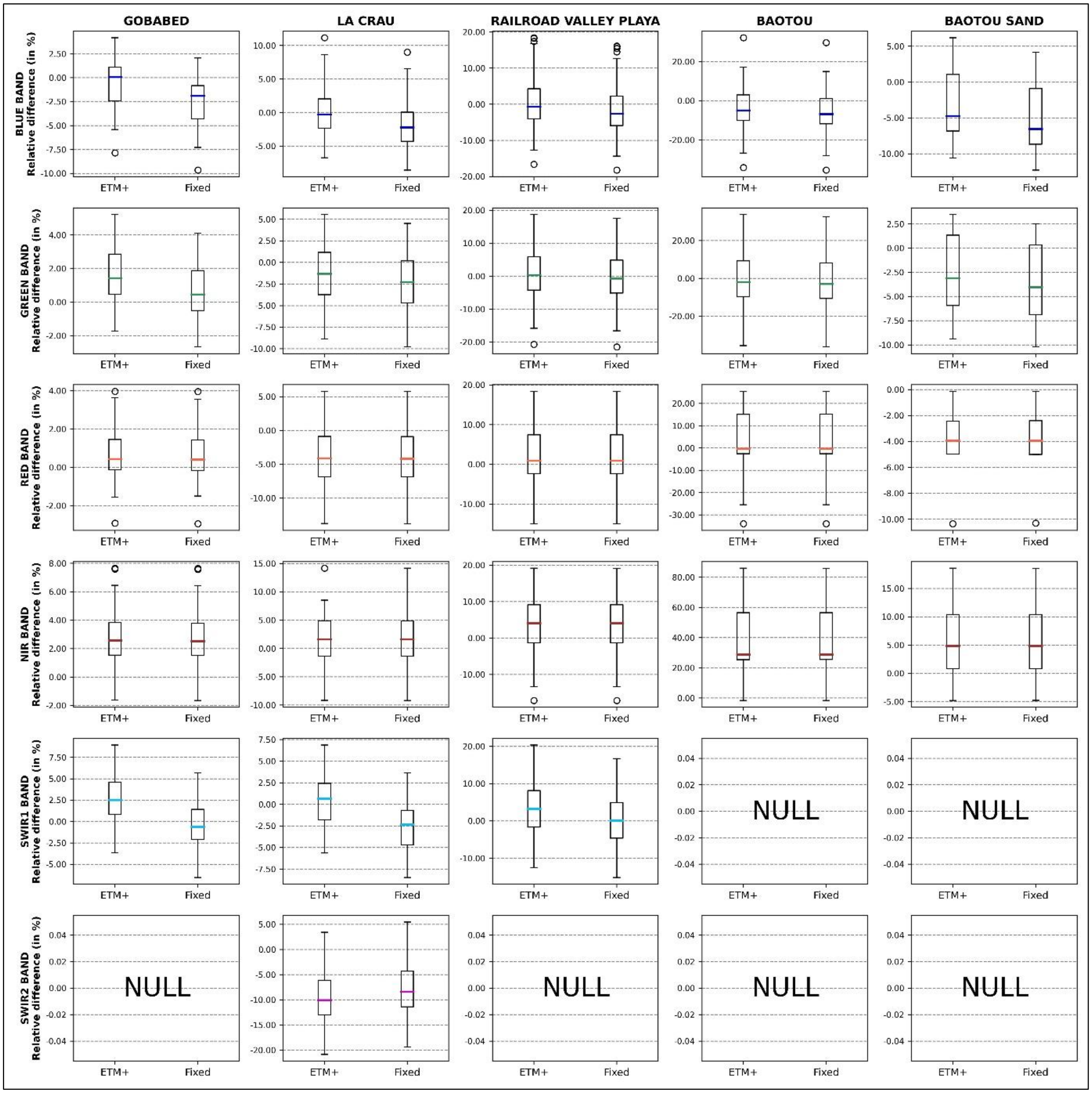

Figure 1 – Relative difference for ToA reflectance of the original and corrected ETM+ sensor data in relation to the reference values of the five RadCalNet portal sites.

The relative difference (error) results for the five RadCalNet sites in the six spectral bands selected are shown in Figure 1. It can be seen that, due to the level of dispersion of the relative differences obtained, the

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Railroad Valley Playa and Baotou sites showed less suitable results for radiometric calibration of ToA reflectance. However, considering that the pixels that make up the ETM+ scenes do not coincide exactly with the RadCalNet calibration regions, it is understood that the pixels that make up the clippers of the scenes analyzed may be influenced by the spectral characteristics of the external vicinity of the calibration region. This issue may interfere with the quantification of errors in the data analyzed, especially at the La Crau, Railroad Valley Playa and Baotou sites, due to the size, geometric shape and geographical location of these regions in the Landsat scenes.

The ToA reflectance data from the ETM+ sensor showed a relative error of less than or close to 5% in most of the scenes corresponding to the time series analyzed, as indicated in the instrument's handbook (USGS, 2019a) (Figure 1 and Table 1).

IV. Discussion

Some factors that may affect the quantification of the results obtained (uncertainties) were not considered in the analyses carried out. These are: (a) the time between obtaining the ETM+ scenes and the RadCalNet records, which varies between 0 and 15 minutes; and (b) the viewing angle of the imaged targets, considering that the RadCalNet data are available for the nadir viewing angle and the ETM+ scenes are not. As the purpose of this study is to compare the results and, consequently, assess whether the proposed approach can positively impact the accuracy of the ETM+ ToA reflectance values, these uncertainty factors would not significantly affect the conclusions and were therefore not considered during the approach taken.

The results of the analysis of the accuracy values complement the study by Müller and Vibrans (2024) on the impact of using SIM/SORCE solar spectra on the radiometric correction of the ETM+ sensor's ToA reflectance products. The authors found that the impacts were significant, but did not conclude whether they were positive, i.e. whether they contributed to improving the accuracy of the products or not. The results obtained here make this assessment possible and indicate that these impacts may be positive for the products in the green, red, NIR, SWIR-1 and SWIR-2 bands.

The quantification of the impacts on the accuracy of the scenes, represented by the EAP parameter (see supplementary materials), is in line with the average percentage differences between the SIM/SORCE daily solar spectra and the respective reference ESUN values suggested for the ETM+ radiometric correction (Müller; Vibrans; Pinto, 2024; Müller; Vibrans, 2024). In this sense, the similarity between the SIM/SORCE solar spectra

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in the red and NIR regions with the respective reference ESUN values justifies the low impacts on the accuracy of these spectral bands.

In addition, it is important that the methodology proposed in this study also be carried out with solar spectra from more modern and accurate instruments than SIM/SORCE, such as the TSIS missions, for example. In this way, it will be possible to establish more accurate confidence intervals for the impacts on the accuracy of the corrected scenes.

With regard to the temporal stability of ETM+ data, the results suggest that a small (non-significant) portion of this stability, both in terms of accuracy and ToA reflectance, can be improved by using solar spectra obtained daily by instruments not coupled to the sensor system itself. Therefore, this approach could be an alternative to contribute to the radiometric calibration of sensors that do not have instruments integrated into their system to record irradiance in orbit (radiometric calibration based on radiance), recovering a portion of the variability caused by non-seasonal solar events.

The use of accuracy (or error) to assess the temporal stability of the scenes obtained was an alternative to minimize the effects of the variability of the spectral characteristics of the targets imaged over time. In this way, it was possible to isolate the effects of sensor instability from the variance corresponding to the targets observed during the analysis.

Müller and Vibrans (2024) concluded that the variability caused by solar cycles in ToA solar irradiance impacts the radiometric calibration of ToA reflectance from multispectral sensors. As the data available for the time series analyzed in this study are small for some sites and covers a period of less than one solar cycle, it is possible that the indicators obtained are underestimated in relation to the impacts caused by solar cycles. In addition, the temporal coverage of the data used coincided with the final period of solar cycle number 24, outside the solar maximum. At this stage, the variations in solar irradiation in the ToA were stabilizing and did not include periods with more significant variations due to extreme solar activity. It is probable that future studies with greater temporal coverage will obtain more promising indicators to support the feasibility of implementing this approach in radiometric calibration processes.

Finally, this study provides input to encourage discussions on the use of daily solar spectra obtained by instruments external to the sensor system in the calibration and radiometric correction of multispectral images. The results presented here suggest that this approach may be favorable for improving accuracy and temporal stability in some spectral regions. However, further studies are needed to analyze which ToA spectral solar irradiance measurement instrument is most suitable for this purpose.

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V. CONCLUSSION

According to the results obtained, it can be affirmed that there is insufficient evidence to refute the study hypothesis that the use of external solar spectra contributes to improving the accuracy and temporal stability of the ToA reflectance obtained by multispectral sensors whose radiometric correction is based on radiance values. Although the impacts found in the radiometrically corrected data are not statistically significant, we found that the proposed approach can contribute a small percentage to improving the accuracy of the ToA reflectance values analyzed, both in terms of the accuracy of the records and their temporal stability. The main conclusions are threefold: (i) the radiometric calibration of the ToA reflectance of multispectral remote sensors that do not have solar diffuser panels attached to their system can be improved by using solar spectra obtained daily by instruments external to the calibrated sensor; (ii) the use of solar spectra obtained by the SIM/SORCE instrument in the correction and radiometric calibration processes of the ToA reflectance of the ETM+ sensor can help to improve the accuracy and temporal stability of these values; (iii) the use of daily solar spectra obtained by instruments external to the calibrated sensor systems helps to recover the temporal instability associated with non-seasonal solar activity phenomena.

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