Uncertainty Evaluation of the TOA Radiance Predicted by MODTRAN-5

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Abstract. The reflectance-based approach is a calibration method in which in-situ radiometric measurements of a selected target on the Earth surface and atmospheric parameters are used as input into a radiative transfer model for estimating a top-of-atmosphere (TOA) radiance. However, an estimate of the TOA radiance is incomplete unless complemented with its uncertainty. This work described a methodology for predicting TOA radiance with an associated uncertainty. Two different methods of uncertainty propagation were applied: ISO-GUM and Monte Carlo. In both methods the TOA radiance was calculated using the atmospheric radiative transfer code MODTRAN. Vicarious calibration data collected on August 21st, 2014 at Atacama Desert, Chile and on July 25th, 2014 at Luís Eduardo Magalhães, Brazil were used to evaluate the methodology. The results, for the wavelength between 350 to 2400nm, showed that using an agricultural area covered by soil surface (Brazil) the final uncertainty of the TOA radiance ranged from 1.0% to 9.2%; and using a desert surface (Chile) the final uncertainty ranged from 0.7% to 4.5%. The results also showed that the overall uncertainty using Monte Carlo simulations were smaller than the root sum of squares of each parameter (ISO-GUM), suggesting that there is correlation among some parameter that is not take into account when the data are considered independent.

Keywords: calibration, MODTRAN, reflectance-based approach, TOA radiance, uncertainty.

1. Introduction

Vicarious calibration is a technique that attempts to predict the radiance at the sensor, i.e. top-of-atmosphere (TOA) radiance, over a selected test site on the Earth's surface. It has become widely adopted as the means to provide independent assurance of the quality of remotely sensed data (DINGUIRARD and SLATER, 1999; BIGGAR et al., 2003). Perhaps, the most two methods used is the reflectance-based approach and cross-calibration method. This current work focuses on the reflectance-based approach method.

The reflectance-based approach requires ground reflectance (or radiance) and atmospheric measurements coincident with the sensor overpass over a selected surface. The in-situ measurements are used to constrain a radiative transfer code that predicts TOA radiance, which is compared to the radiance reported by the sensor system. The atmospheric radiative transfer code adopted here was the MODerate resolution atmospheric TRANsmission

(MODTRAN) (BERK et al., 2011). The reflectance-based approach was effectively implemented by several research groups and applied to several Earth observing sensors such as ETM+/Landsat-7, OLI/Landsat-8, ASTER/Terra and Hyperion/EO-1 (THOME, 2001; CZAPLA-MYERS et al., 2015; MCCORKEL et al., 2013).

It is important to emphasize that confidence in a measured value requires a quantitative report of its quality, being necessary the evaluation of the uncertainty associated with the value (PINTO et al., 2016). Then, an estimate of the TOA radiance is incomplete unless supplemented by its uncertainty. Here, a methodology for evaluating the uncertainty of the TOA Radiance predicted by MODTRAN-5 has been presented. To achieve this goal it was applied and compared two different methods of uncertainty propagation: ISO-GUM and Monte Carlo. A vicarious calibration data collect on August 21st, 2014 at Atacama Desert, Chile and July 25th, 2014 at Luís Eduardo Magalhães, Brazil were used to evaluate the methodology.

2. Reflectance Factor and Atmospheric Parameters

The first component of the reflectance-based approach is the surface reflectance factor at the time of sensor overpass. In **Figure 1a** is presented the spectral reflectance factor from the two sites: west part of the Bahia State (Luís Eduardo Magalhães), Brazil and Atacama Desert, Chile. In addition, the coefficient of variation (CV) defined as the ratio between the standard deviation and the average is shown as a percentage in **Figure 1b**. The gaps around 1400 and 1800 nm are due to strong water vapor absorption near those wavelengths and the 2400-2500 nm spectral region shows larger variability primarily due to decreasing signal level. The line representing the Atacama Desert did not present gaps in both the reflectance factor and the coefficient of variation curve in the spectrum regions strongly affected by water vapor absorption. This means that the amount of water is very low in this region.

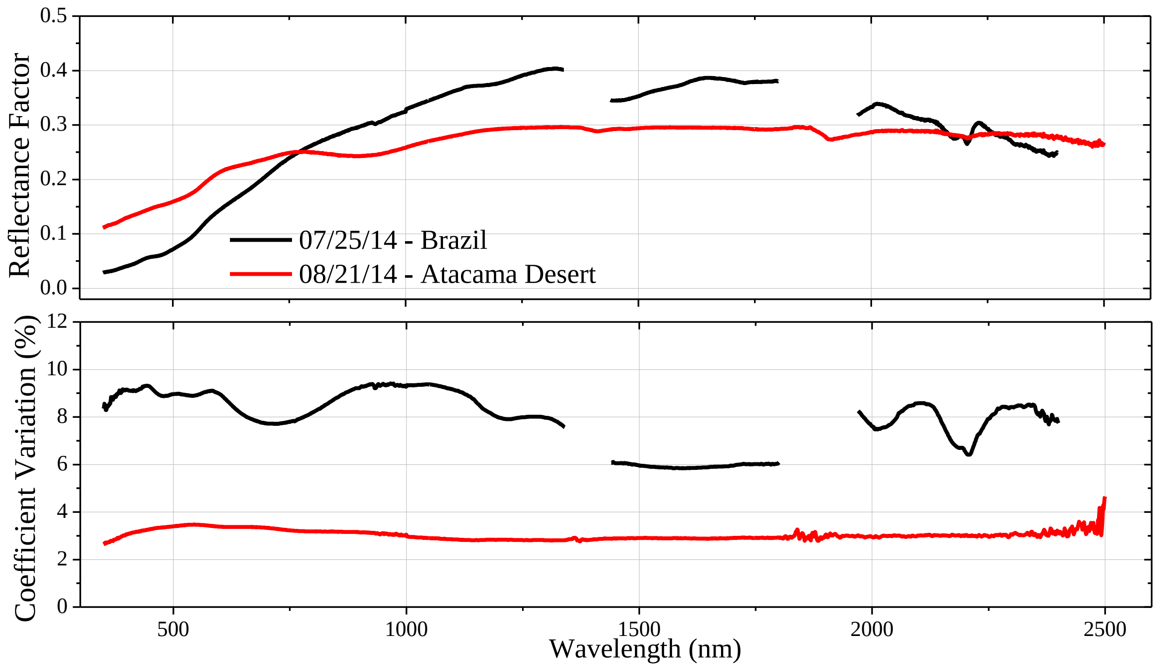

Figure 1. In (a) Spectral reflectance results of the reference sites; and (b) surface coefficient of variation in percentage.

Atmospheric characterization data are collected at the same time as the surface reflectance measurements. In **Table 1** is presented some atmosphere parameters acquired during the field campaigns in Chile and in Brazil sites. Further information about these field campaigns can be found in Pinto et al. (2015) and Pinto (2016).

The aerosol optical depth (AOD) is a measure of radiation extinction due to the interaction of radiation with aerosol particles in the atmosphere. AOD lower than 0.1 indicates clear sky, whereas value of 1 corresponds to very hazy conditions (GRO et al., 2013). In Brazil the AOD ranged from 0.0105 ± 0.0006 (870 nm) to 0.0324 ± 0.0006013 (1020 nm). The AOD in Chile, Atacama Desert, were between 0.0328 ± 0.0011 (870 nm) to 0.0835 ± 0.0012 (440 nm).The amount of water for each site is also shown in **Table 1**. As expected, the water content in the Atacama Desert was minimal (0.2986 ± 0.0010 g/cm^2). In Brazil the water content was higher: 3.402 ± 0.007 g/cm^2.

Table 1: Atmosphere parameters during the measurements of atmospheric conditions made at Atacama Desert, Chile and Luís Eduardo Magalhães, Brazil.

Parameter	Luís Eduardo Magalhães, Brazil July 25th, 2014	Atacama Desert, Chile August 21st, 2014
Water (g/cm^2)	3.402 ± 0.007	0.2986 ± 0.0010
VIS (km)	53 ± 5	37.4 ± 2.4
AOD 550nm	0.029 ± 0.012	0.076 ± 0.013
AOD 440nm	0.0212 ± 0.0015	0.0835 ± 0.0012
AOD 670nm	0.0243 ± 0.0009	0.0643 ± 0.0014
AOD 870nm	0.0105 ± 0.0006	0.0328 ± 0.0011
AOD 1020nm	0.0324 ± 0.0006	0.0721 ± 0.0009

3. Methodology

The atmospheric parameters and the reflectance factor surface were estimated with the associated uncertainties as described in the previous section; therefore, it is also necessary to verify the impact of the input parameters uncertainties on TOA radiance predicted by MODTRAN. To achieve the goal, the five most important sources of uncertainty were considered: (i) the reflectance factor of the surface – RF; (ii) the aerosol optical depth – AOD; (iii) the water vapor column abundance – Water; (iv) the horizontal visibility – VIS; and (v) the ozone – O_3. The ozone column considered was the default of MODTRAN.

This work describes a methodology for predicting TOA radiance with an associated uncertainty. Two different methods of uncertainty propagation were applied and compared: ISO-GUM and Monte Carlo Simulation. **Figure 2** illustrates these both methodologies. The Monte Carlo approach is known as the propagation of distributions method and the ISO-GUM technique as the propagation of uncertainty method.

ISBN: 978-85-17-00088-1

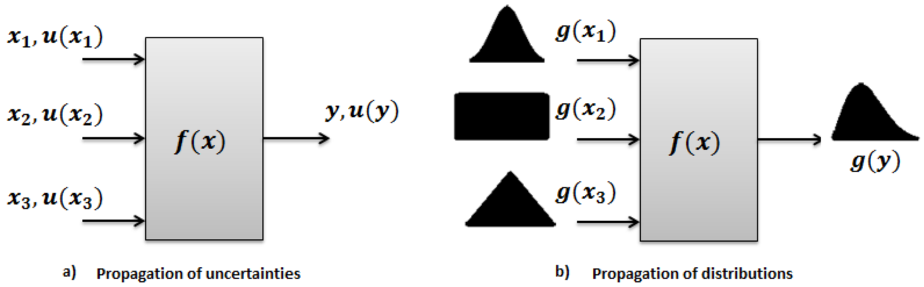

Figure 2: Illustrations of the methodologies of (a) propagation of uncertainties, where x_1, x_2 and x_3 are input quantities, $u(x_1)$, $u(x_2)$ and $u(x_3)$ are their respective uncertainties and y and $u(y)$ are the measurand and its uncertainty, respectively; and (b) propagation of distributions, where $g(x_1)$, $g(x2)$ and $g(x_3)$ are the distribution functions of the input quantities and $g(y)$ is the distribution function of the measurand.
Source: Couto et al. (2013).

3.1 ISO-GUM Method

To determine the impact of the reflectance factor uncertainties on MODTRAN using the ISO-GUM method, all the other input parameters were held fixed. Then, the MODTRAN was run for two cases: (i) maximum reflectance factor (average reflectance added the uncertainty – + 1σ); (ii) minimum reflectance factor (average reflectance subtracted the uncertainty – - 1σ). The next step was to determine the absolute difference between these two results and divide it by two. The division by two is required because the uncertainty is always “plus or minus (±)” the mean value. The value obtained from this division would be the "sensitivity" of MODTRAN to the maximum and minimum values of the reflectance and, then, it was considered the impact of the reflectance factor uncertainties on MODTRAN.

To determine the uncertainties of the other parameters on MODTRAN (aerosol optical depth, water vapor column abundance, ozone and horizontal visibility) the same procedure was applied. The parameter of interest always varied (maximum and minimum) while the other inputs were kept fixed.

After all uncertainties have been calculated the overall uncertainty of the TOA radiance (or TOA reflectance) predicted by MODTRAN was estimated using **Equation 1** (root sum of squares of each factor):

$$\sigma_{L_{TOA-MODTRAN}} = \sqrt{(\sigma_{RF})^2 + (\sigma_{AOD})^2 + (\sigma_{Water})^2 + (\sigma_{O3})^2 + (\sigma_{VIS})^2} \quad (1)$$

3.2 Monte Carlo Method

The Monte Carlo method is a computational algorithm that depends on random and repeated sampling to obtain approximate results. Monte Carlo simulation allows determines some possible outcomes. This method is based on random numbers generation for each primary quantity, according to their probability distribution function (PDF) and propagated through a mathematical model of measurement. This propagation consists of assuming a distribution for each input quantity (e.g., uniform distribution, normal or triangular). Then, these distributions are propagated M times (where M is the number of iterations) by a mathematical model of measurement, and a new distribution is generated as a result.

The Monte Carlo method was used here to randomly sample the various factors (surface reflectance, AOD, VIS, water vapor, and ozone content) within their respective error ranges and following a normal probability distribution for input into the radiative transfer code (MODTRAN-5).

ISBN: 978-85-17-00088-1

The number of iterations influences the accuracy of the results obtained by Monte Carlo simulation. Some tests were conducted to evaluate variations in the results in relation to the number of iterations. It was chosen to perform 100 iterations in each variable randomly generated. In **Figure 3** can be observed the randomly values generated (normal probability distribution) for the variable water and for both reference surfaces (Brazil and Chile). Note that the mean and standard deviation of **Figure 3** histogram is equal to the water values shown in **Table 1**.

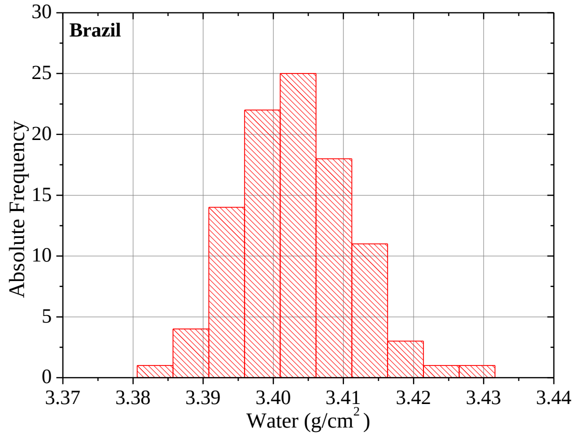

Figure 3: Histogram of random numbers generated for water content. In (a) Brazil site and (b) Chile site.

4. Results and Discussion

The five sources of uncertainties estimated using ISO-GUM and Monte Carlo methods are presented in **Figure 4.** In this figure is also presented the difference between the results obtained from both methods. The graphics located on the right of the **Figure 4** shows the results achieved from the data collected in Chile site. The graphics on the left are the results obtained from the data collected in Brazil site.

Every source of uncertainty depends on the wavelength. The uncertainties using both evaluations of uncertainty methods present similar spectral behavior. The values of the source of uncertainty were also similar, except for the reflectance source of uncertainty. The difference between the results achieved with both methods using the site in Chile was low: from 0.00 to 0.06 W/(m^2·sr·µm) (except for the reflectance source of uncertainty). On the other hand, the difference between the results reached with both methods using the site in Brazil was slightly higher, ranged from 0.00 to 0.29 W/(m^2·sr·µm) (except for the reflectance source of uncertainty).

The main source of uncertainty considering the both calibration sites and both methods, was the surface reflectance factor. The largest difference was also found for the source of uncertainty related to reflectance: from 0.00 to 2.73 W/(m^2·sr·µm) in Brazil site and from 0.00 to 1.35 W/(m^2·sr·µm) in Chile site (see **Figure 4c** and **Figure 4f**, respectively).

ISBN: 978-85-17-00088-1

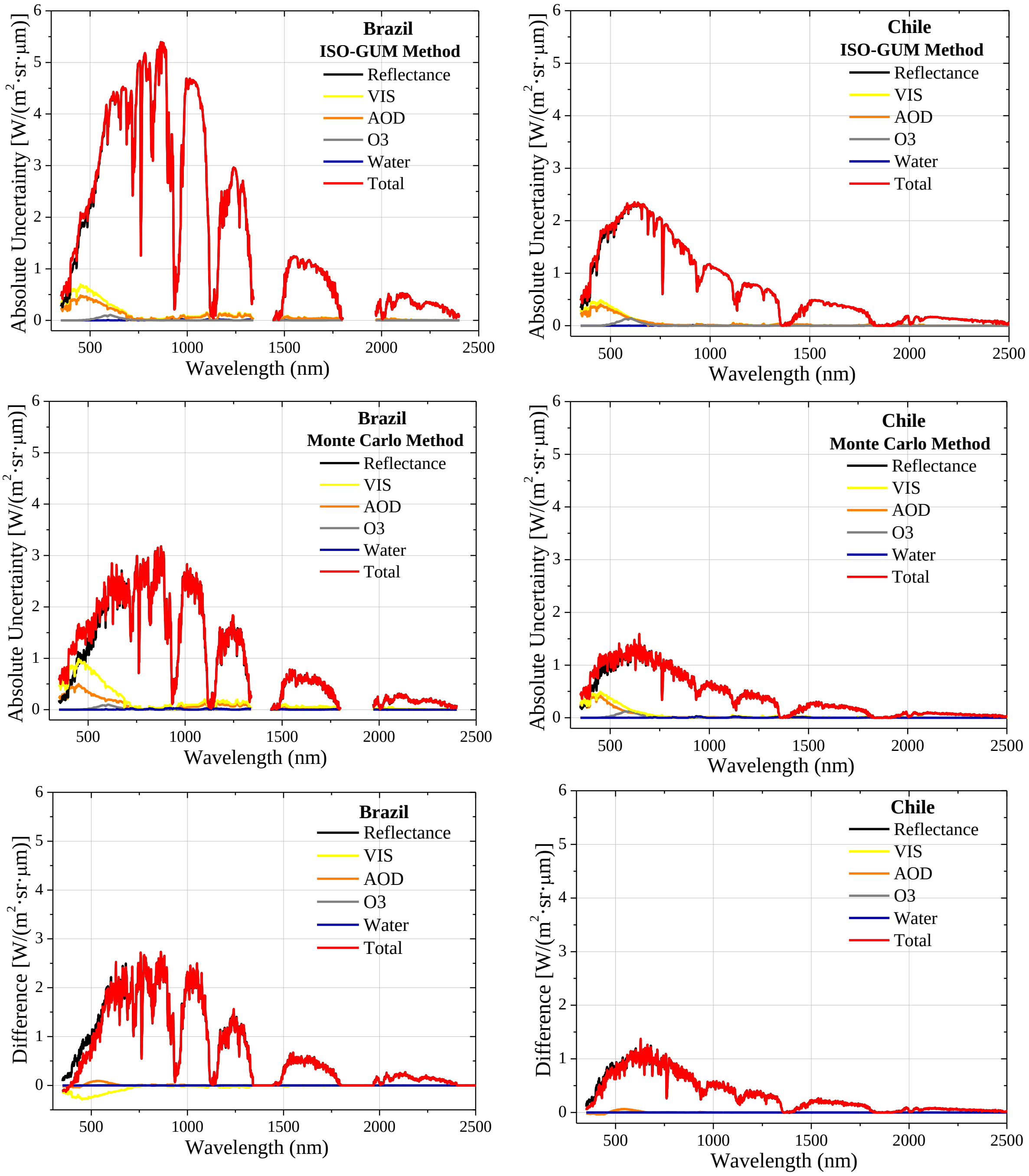

Figure 4: In (a), (b), (c) and (d) TOA radiance uncertainties predicted by MODTRAN. In (e) and (f) the difference between the uncertainties obtained using ISO-GUM and Monte Carlo methods.

Figure 5 shows the TOA radiance values predicted by MODTRAN and their final relative uncertainty (in percentage). The reference surface in the Atacama Desert, Chile presented the lowest final uncertainties: between 0.65 and 4.50% using ISO-GUM uncertainty framework and between 0.83 and 3.34% using Monte Carlo simulations. The reference surfaces in Brazil presented higher final uncertainty from 1.01 to 9.18% using ISO-GUM method and from 1.26 to 5.91% using Monte Carlo method.

One hypothesis that explains the divergence between the results reached with the methods is that the ISO-GUM method performs the propagation of uncertainty considering that the variables are statistically independent (see **Equation 1**). On the other hand, the Monte Carlo simulations method takes into account the correlations, through the random generation of the five variables. In fact, the five variables included here are not truly independent of each other. For example, the VIS is deeply affected by the AOD. In addition, increasing or decreasing the surface reflectance may affect the radiance reflected by aerosols (Chen et al., 2015). Therefore, the overall uncertainty should include some measure of covariance between each pair of variables.

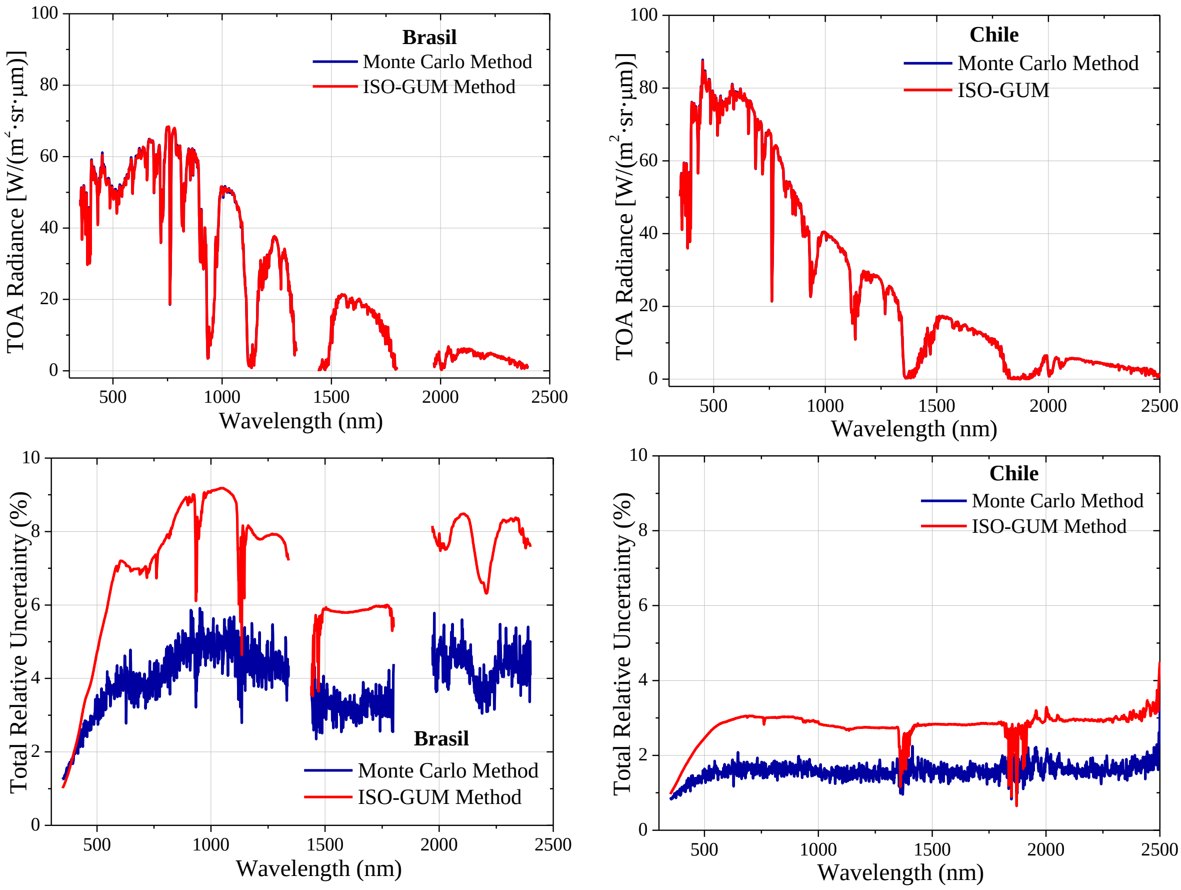

Figure 5: In (a) and (b) TOA radiance predicted by MODTRAN; and (c) and (d) its final relative uncertainty (in percentage) using Brazil and Chile sites, respectively.

5. Conclusions

The uncertainty results of the TOA radiance predicted by MODTRAN-5 estimated with the ISO-GUM uncertainty framework and the Monte Carlo method presented difference. It was revealed that the overall uncertainty using Monte Carlo simulations is smaller than the root sum of squares of each variable (ISO-GUM). The main source of uncertainty, considering both calibration surfaces and both methods, was the surface reflectance factor, which presented the largest difference between the methods. One hypothesis that could explain the differences between the results is the correlation between the five variables considered (reflectance, AOD, Water, VIS and O_3). In this work, the method based on ISO-GUM considers that the variables are uncorrelated (each variable is independent) and, on the contrary, the Monte Carlo considers some correlation. Thus, in future studies, it is recommended evaluates the real correlation between the input variables and also perform more iteration with the Monte Carlo method.

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