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SPECTRAL UNIFORMITY EVALUATION OF REFERENCE SURFACES FOR AIRBORNE AND ORBITAL SENSORS ABSOLUTE CALIBRATION

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ABSTRACT. The extraction of quantitative information from data collected by either airborne or orbital electro optical sensors is only possible through a well-performed absolute calibration. The most common method of in-flight absolute calibration uses a reference surface. One of the most critical steps to implement this method is the reference surface characterization, which must be spectrally uniformity, among other features. This study presents the methodology used to assess the spectral uniformity of two potential areas for in-flight sensor calibration. Two surfaces were studied: (a) an area in Brazil of bare soil (quartz sand) and (b) Tuz Gölü salt flat in Turkey considered by the CEOS (Committee on Earth Observation Satellites) an official area for orbital sensors calibration. Radiometric measurements were carried out at various sampling points in these two areas. In addition, the study aims to describe and determine some of the main uncertainties sources involved in this process. According to the statistical criteria adopted, both reference surfaces have not been considered spectrally uniform.

Keywords: spectral uniformity, electro-optical sensors, absolute calibration.

RESUMO. Para que seja possível extrair informações quantitativas de dados coletados por sensores eletro-ópticos aerotransportados ou orbitais é necessário o conhecimento sobre a sua calibração absoluta. O método mais difundido de calibração absoluta em voo é aquele fundamentado na utilização de uma superfície de referência em campo. Uma das etapas mais críticas na execução desse método é a caracterização da superfície de referência que deve apresentar, entre outras características, uniformidade espectral ao longo de sua extensão. Assim, este trabalho apresenta a metodologia utilizada na avaliação dessa uniformidade em duas superfícies potenciais para calibração de sistemas sensores. As duas superfícies utilizadas foram: (a) uma área no Brasil, constituída por solo exposto (areias quartzosas) e (b) salar Tuz Gölü na Turquia, considerada pelo CEOS (*Committee on Earth Observaton Satellites*) como uma área oficial para calibração de sensores. Foram realizadas medições de reflectância em campo, em vários pontos amostrais, nestas duas superfícies. Além disso, o trabalho teve como objetivo descrever e determinar algumas das principais fontes de incertezas envolvidas neste processo. Com os valores de reflectância e suas respectivas incertezas, obtidas nos diversos pontos amostrais, verificou-se, segundo os critérios estatísticos, que as duas superfícies de referências não são espectralmente uniformes.

Palavras-chave: uniformidade espectral, sensores eletro-ópticos, calibração absoluta.

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INTRODUCTION

The development of electro-optical sensors has allowed a differentiated and diversified study of Earth's surface. Some sensors have the ability to provide high resolution spectral, radiometric and space images, from which it is possible to get detailed information of objects scattered over the earth surface. However, a high degree of reliability in the absolute calibration of the sensor is necessary in order to infer the geophysical and biophysical properties of the studied objects from the quantitative approaches to be explored (Biggar et al., 1994).

Several in-flight radiometric calibration methods have been proposed for these sensors. Methods based on the use of reference surfaces have been widely used for orbital sensors, such as the Enhanced Thematic Mapper Plus (ETM+) (Thome, 2001) and the High Resolution CCD Camera (CCD) of CBERS-2 (Ponzoni et al., 2008). This calibration method can also be used to calibrate airborne sensors.

The first and most critical stage of this calibration method is to choose a reference surface with specific, uniform and stable characteristics (Scott et al., 1996), which can be divided into two groups: (a) characteristics related to atmospheric and geographic issues, that is, the region must have low cloudiness rates, high altitude and be flat; and (b) the physical characteristics, such as high reflectance values, isotropy and uniformity over a desired spectral range, all of which should be stable over time. Furthermore, it is also desirable that the surface be easily accessible by land.

According to Thome (2001), no surface area is able to fulfill all these requirements; however, there are some places that meet part of the requirements, and have already been used for sensor calibration (Milton et al., 2009): White Sands Missile Range (New Mexico), Railroad Valley Playa and Lunar Lake (Nevada) in the United States and Salar de Uyuni in Bolivia. Recently, Tuz Gölü salt flat, in Turkey, has been pointed out as an appropriate surface for radiometric calibration of the sensors.

In order to identify a reference surface it is necessary to perform a series of field radiometric measurements, whose results should be as reliable as possible. For this, a statistical analysis of the data is performed to establish the radiometric magnitude and the uncertainty resulting from these measurements (ABNT & INMETRO, 2003), as well as to verify if the area characteristics meet the criteria of a reference surface for in-flight calibration. Moreover, for a correct determination of the magnitude and uncertainties related to the characterization of the reference surface, it is necessary to define the methodology to be followed during field measurements.

The objective of this study is, therefore, to present the methodology used to evaluate the spectral uniformity of the potential reference areas for sensor calibration. The methodology was applied on two surfaces, the first area is an agricultural region in western Bahia, preselected according to atmospheric and geographic criteria and the second, a region in central Turkey named Tuz Gölü. The paper also describes the major sources of uncertainty associated with the radiometric measurement process. In addition, the results obtained for both surfaces were compared.

STUDY SITES

In Brazil there are no areas that meet all the requirements to be characterized and used as reference areas for in-flight calibration (Ponzoni et al., 2008). However, in the far western region of Bahia, it is possible to identify some areas used for agricultural plantations that partially meet these requirements. Ponzoni et al. (2008), for example, performed absolute calibration of the sensor CCD/CBERS-2 in an area near the town of Luis Eduardo Magalhães (BA). According to the authors the region has the following characteristics: (a) low cloudiness rates; (b) altitude of approximately 850 m; (c) mainly quartz sand surface that has high reflectance; (d) the agricultural calendar is followed every year, and therefore, it is possible to locate a specific calibration site with the same characteristics at a particular time of the year; and (e) the reference surfaces are located in farms with easy road access.

At the time of the study, an area in Santa Luzia farm, in Correntina (BA), had a set of characteristics that allowed the radiometric field measurements to take place in April, 2010. Subsequently, in August of the same year, data were collected on the surface area in Tuz Gölü, Turkey, which is a salt flat located at approximately 910 m altitude and during the dry season has very high reflectance. Currently, there are only eight official surfaces according to the CEOS (Committee on Earth Observation Satellites) to calibrate sensors and the Tuz Gölü salt flat is one of them.

REFLECTANCE FACTOR

Reflectance is the ratio of the total amount of electromagnetic radiation (REM) reflected by a surface to the total amount of REM incident on the surface. However, reflectance cannot be measured directly, because the infinitesimal elements of the solid angle do not include measurable amounts of radiant flux (Schaepman Strub et al., 2006). Thus, due to technical difficulties to measure reflectance in either field measurements or laboratory, the reflectance factor (RF) is the equivalent used in practice (Milton, 1987). This quantity is the ratio of spectral radiance reflected from

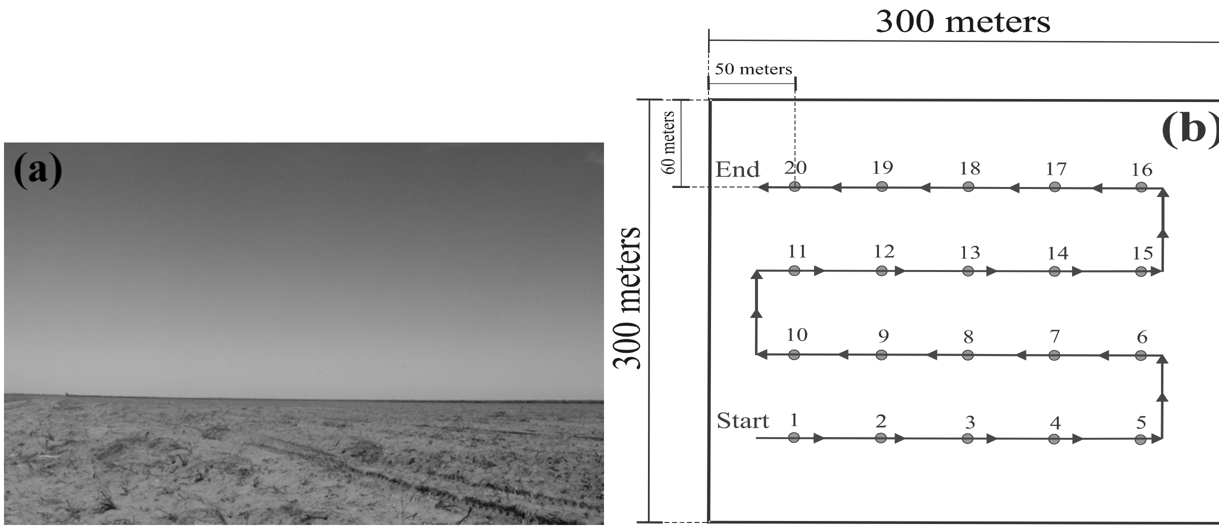

Figure 1 – (a) reference surface; and (b) schematics of the 20 points where the radiometric data were collected.

a sample (target) to the spectral radiance that would be reflected by a perfect diffuse Lambertian surface, under the same lighting and observation conditions, according to equation (1) (Milton, 1987):

$$FR_{target} = \frac{L_{target}}{L_{panel}} \tag{1}$$

where L_{target} is target radiance and L_{panel} is the radiance of a reference plate (presumably Lambertian). For simplification purposes, spectral and angular dependence of RF was omitted.

RADIOMETRIC FIELD MEASUREMENTS

Reference surfaces are characterized by radiometric measurements in order to determine average RF representative of the surface and by evaluating the spectral uniformity along its length or in part of it. Spectral uniformity is characterized by reflectance values and, in general, evaluated by comparing the values measured in a few sample points on the reference surface. The methodologies used in the field work for the two studied sites (a) the agricultural area in Correntina, Bahia; and (b) the salt flat in Tuz Gölü, Turkey are described below.

Brazil

A reference surface of approximately 300 by 300 m, with quartz sands, in Santa Luzia farm, in Correntina, was used for the radiometric measurements (Fig. 1a). Radiometric data were collected in the twenty points defined on this reference surface according to Figure 1b.

The measurements were performed using a FieldSpec Pro spectroradiometer from ASD (Analytical Spectral Devices) (ASD, 1999), which operates in the 350-2500 nm spectral range. The reference plate used was the Spectralon from Labsphere (LABSPHERE, 2009). In order to determine the conditions of the instruments and their respective contribution to the uncertainty of the final measurements, trials were conducted before and after field work, in the Laboratory of Radiometry and Characterization of Electro-optical Sensors (*Laboratório de Radiometria e Caracterização de Sensores Eletro-ópticos*, LaRaC) of Instituto de Estudos Avançados (IEAv). In the experiment conducted at LaRaC, the Spectralon reference panel and ASD FieldSpec Pro spectroradiometer used in the field were evaluated against similar equipment belonging to LaRaC, which were recently characterized by the manufacturer (Pinto, 2011).

Field work was conducted on April 13, 2010, from 9h to 10h. The measurements were performed by two operators and Figure 1b shows the path taken by the operators on the reference surface. The FieldSpec Pro spectroradiometer was operated manually, with the collection unit held vertically toward the ground, with the operator facing the sun, thus avoiding the projection of his shadow on the surface to be effectively measured. The distance between spectroradiometer collection unit and the target was approximately 1.3 m. The reference plate was kept on a tripod near the point being characterized, keeping the operator as far as possible from both, plate and collection unit (with field of view of 8°). The measurements were performed in FieldSpec Pro reflectance mode; therefore, first the reference plate is measured and stored in the device memory then, the target is also measured, and the equipment calculates radiance ratio of the target to the reference plate (see Eq. 1). Thus the RF of the reference

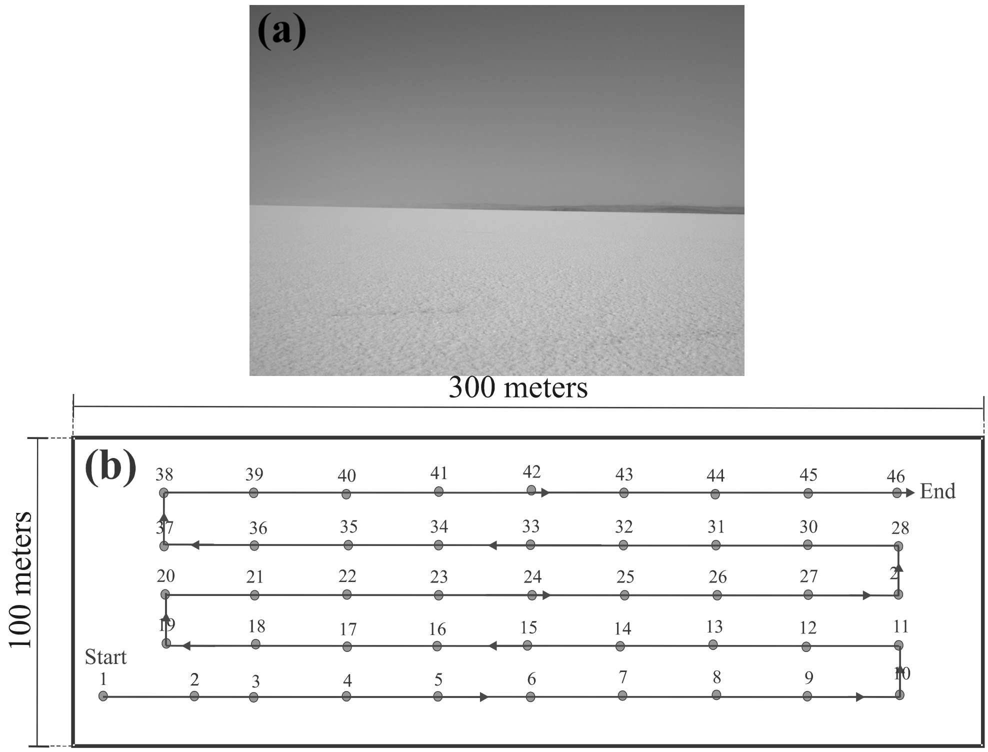

Figure 2 – (a) Tuz Gölü reference surface; and (b) schematic representation of the sample points.

surface, RF_{target}, is determined by the equipment. Four reflectance measurements were conducted on the reference plate, the target and again four more on the reference plate. The number of measurement repetitions was chosen in order to assess more precisely the RF and the uncertainty (Type A, statistics) associated with the data; while these 4 measurements were considered feasible within the one hour time slot fixed as optimal for the trials.

Turkey

An area of 100 by 300 m (Fig. 2a) with 46 sample points, see Figure 2b, was selected in Tuz Gölü salt flat, while adopting the continuous mode for radiometric measurements. The field work in Turkey was performed on August 18, 2010, from 10:30h to 11:30h. The radiometric measurements were also performed using a ASD FieldSpec Pro, and a Spectralon reference plate that belonged to the Council for Scientific and Industrial Research (CSIR). Generally, radiometric field measurement conditions were similar to those performed in Brazil. The only difference was that in Turkey five target measurements were performed on each sample point followed by five reference plate measurements, adopting the continuous method.

DATA TREATMENT

Spectral uniformity of each reference surface was evaluated taking into consideration the radiometric data collected on the sampling points. Thus, supposedly, the measurements on each sampling point should have Gaussian distribution characterized by the mean and standard deviation. Therefore, if the surface is uniform these measurements should have the same mean and standard deviation, determined by statistical tests comparing the two parameters. Firstly, the variances of each sample point are compared by the homoscedasticity test. Subsequently, if the variances are homoscedastic (statistically identical), the means are compared using the chi-square test. The flowchart in Figure 3 shows the methodology used to evaluate spectral uniformity.

The first step was to analyze the consistency of the raw data collected on each sample point in the surface. This was done in order to detect outliers as well as bias in the raw data. We discarded data with potential problems that could be attributed to reading errors or mishandling of the equipment. Then, it was checked whether the data were consistent and showed no behavioral bias. Finally, the mean, the standard deviation and the standard deviation of the mean for each sample point were determined (Bevington & Robinson, 2003).

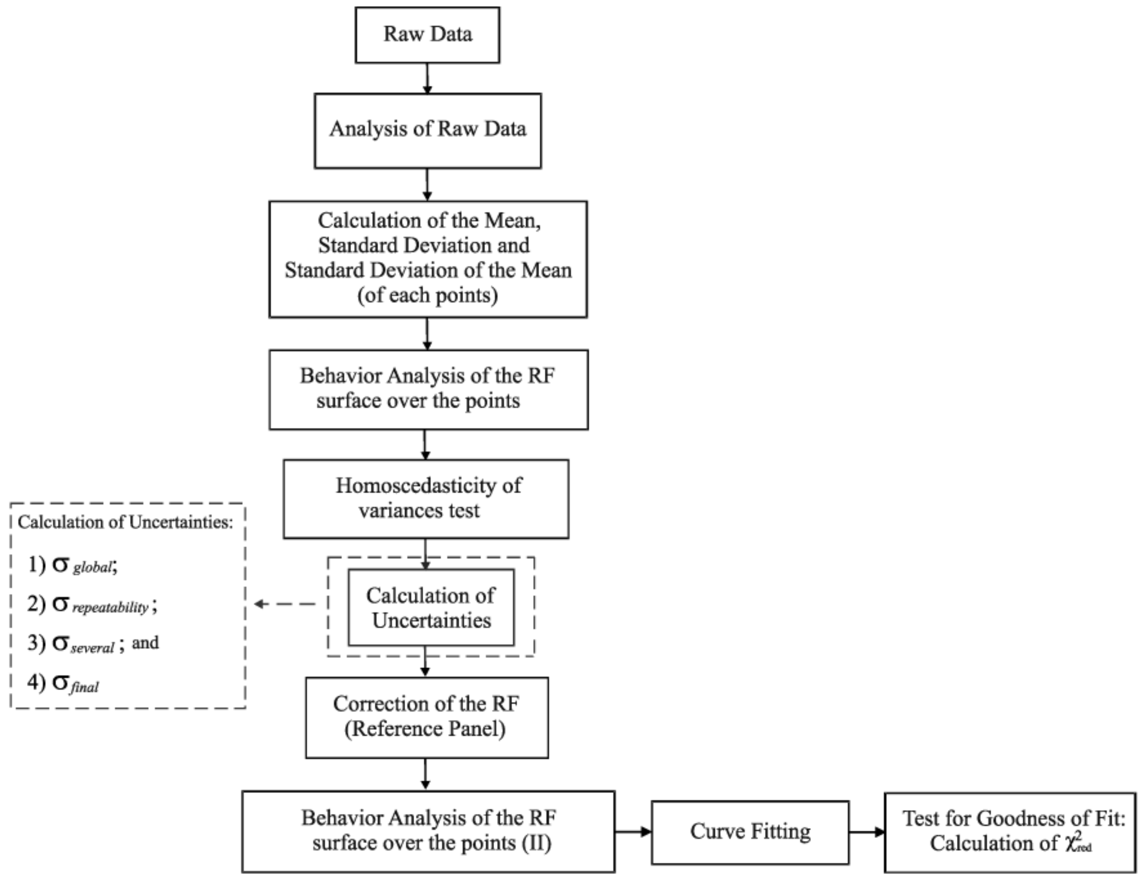

Figure 3 – Flowchart of the methodology used to evaluate spectral uniformity of reference surface.

Both measurements in Tuz Gölü and in Brazil were performed in the reflectance mode of the FieldSpec Pro. So, the RF of the reference surface, RFtarget was determined by the equipment and the statistical uncertainties are the actual standard deviation of the mean from the obtained RFs (ABNT & INMETRO, 2003).

Thus, RF_{target} values and their statistical uncertainties related to repeatability (standard deviation of the mean) were used to evaluate RF behavior along the sample points. The measurements on the sample points were performed under repeatability conditions, that is, by the same operators using the same equipment, so that for a spectrally uniform surface, the means and data dispersion would be the same for all points. Therefore, before comparing the mean values it was necessary to evaluate homoscedasticity of variances.

Variance homoscedasticity test

To assess homoscedasticity of the variances on each sample point, two criteria were used: (a) Cochran Test; and (b) histogram of the variance sampling distribution. Cochran test compares the largest variance with the others. Variance was determined for each of k sampling points (s_i^2, where $i = 1, 2, 3, 4, \ldots, k$), and all samples were the same size in n measurements. Thus, the value of Cochran is given by (Mendes & Rosário, 2005):

$$C_{calculated} = \frac{s^2_{maximum}}{\sum_i^k s_i^2} \tag{2}$$

where: s_i^2 is the variance estimate of sample i; $s^2_{maximum}$ is the highest value found for variance estimates; and k is the number of sample points.

The critical values for Cochran are tabulated as a function of sample size, n, and the number of samples, k. If the calculated value given by Equation (2) is smaller than the critical value in the table, then the variances are homoscedastic. Otherwise, the variances are heteroscedastic. Furthermore, when the variances are homoscedastic, the sample variance distribution histogram (or probability distribution of the sample variance) looks like a probability density function of the chi-square distribution with $k - 1$ degrees of freedom χ^2_{k-1}.

If these criteria are not met, there is an indication that the variances of the sampling points have different distributions, thus implying that the surface is not uniform. However, if the variances are homoscedastic, it is possible to estimate an average of the standard deviations, which is related to the repeatability uncertainty of the measurements.

Calculation of uncertainties

Measurement uncertainties arise from a combination of several sources because the measurements are influenced by metrological agents, such as: measurement method, operator, environmental conditions, equipment and the sample itself (Mendes & Rosário, 2005). Therefore, uncertainty must be taken into account, in addition to statistical fluctuation of the data and the experimental aspects of the measurement. These uncertainties are grouped into two categories, depending on the method used to estimate its value: Type A, which are the uncertainties evaluated by statistical processes; and Type B, the uncertainties evaluated by non-statistical processes.

If variances are homoscedastic (homogeneous), one can calculate an overall standard deviation, which takes into account the dispersion of the date of all sampling points, according to the following equation:

$$\sigma_{global} = \sqrt{\frac{1}{k \times (n-1)} \times \left[\sum_{1}^{n} (x_n - \overline{x_1})^2 + \sum_{1}^{n} (x_n - \overline{x_2})^2 + \cdots + \sum_{1}^{n} (x_n - \overline{x_k})^2 \right]} \tag{3}$$

where: k is the number of sampling points; n is the number of repetitions on each point; x_n is the value obtained from the repetition n; and $\overline{x_k}$ is the mean value for point k.

Thus, statistical uncertainty (Type A), due to repeatability of measurements, $\sigma_{repeatability}$, is given by the following equation:

$$\sigma_{repeatability} = \frac{\sigma_{global}}{\sqrt{n}} \tag{4}$$

In addition to repeatability, final uncertainty of measurements also considered three other sources of Type B uncertainties: (a) uncertainties related to the reproducibility of the experimental setup geometry; (b) uncertainties related to the equipment; and (c) uncertainties related to the procedure.

As described previously, target and reference plate measurements were performed. Therefore, the data were not only used to obtain RF_{target} but also to estimate RF_{panel} for each point. The uncertainty sources related in (a), (b) and (c) listed above are inherent to the RF_{panel} measurements because: (1) the reference plate was always the same, and its physical characteristics remained unchanged during the measurements; (2) atmospheric conditions remained constant throughout the measurements (approximately 1 hour), and (3) solar zenith angle (illumination angle) influenced very little measurement of panel RF (Höpe & Hauer, 2010).

Thus, the uncertainty called "Various Uncertainties", $\sigma_{various}$, was determined from the RF_{panel} data for each point as follows:

$$\sigma_{various} = \sqrt{\left(\frac{1}{k-1}\right) \times \sum_{1}^{k} (x_k - \bar{x})^2} = \sqrt{(\sigma_{reproducibility})^2 + (\sigma_{instruments})^2 + (\sigma_{procedures})^2} \tag{5}$$

where: k is the number of points; x_k is the mean RF of the reference plate at point k; and $\bar{x}$ is the mean plate RF for k points.

So, final uncertainty, σ_{final}, is given by the summation of the estimated uncertainties:

$$\sigma_{final} = \sqrt{(\sigma_{repeatability})^2 + (\sigma_{various})^2} \tag{6}$$

After both RF_{target} and the final uncertainty were determined, the RF value was corrected in relation to the reference plate used, according to the equation:

$$FR_{corrected} = FR_{target} \times f_{panel} \tag{7}$$

where: f_{panel} is the reflectance factor of the reference plate, which is a calibration coefficient determined from the reference plate used, estimated in laboratory.

To estimate $RF_{corrected}$ uncertainty, the propagation of uncertainty is calculated (Vuolo, 1996) according to the following equation:

$$\sigma_{FR_{corrected}} = FR_{corrected} \times \sqrt{\left(\frac{\sigma_{FR_{target}}}{FR_{target}}\right)^2 + \left(\frac{\sigma_{f_{panel}}}{f_{panel}}\right)^2} \tag{8}$$

where: $\sigma_{f_{panel}}$ and $\sigma_{FR_{target}}$ are, respectively, the uncertainty of f_{panel} and the uncertainty of RF_{target}.

Data adjustments: mean surface RF

After the RF of the reference surface (target) was corrected, Eq. (7), and the new uncertainty was determined, Eq. (8), RF of the surface behavior was reevaluated along the sample points in order to adjust the obtained experimental data. As previously mentioned, if the surface is spectrally uniform, all RF values of the surface along the sample points have the same mean (same mean RF value). Thus, a mean RF value was adjusted for the surface. After this procedure, the quality of the adjustment was evaluated, that is, the similarity degree of the adjusted function with respect to all experimental data was determined. The criterion used for this purpose was the reduced chi-square value, χ^2_{red}, which is useful and adequate to assess the quality of a fit, an in general, a good fit is expected to give χ^2_{red} close to 1. However, in order to assess the quality of the fit, it is necessary to establish a confidence interval that depends on the degrees of freedom of the fit. A more detailed interpretation of χ^2_{red} values is given by Bevington & Robinson (2003) and Drosg (2007). If χ^2_{red} values are within the acceptable range, at a determined significance level, it suggests that the means obtained for each sampling point are homogeneous (equal) and therefore, the reference surface is spectrally uniform. In this situation, the adjusted RF value and its uncertainty can be used as the reflectance of the sampling points of the entire surface. On the other hand, for χ^2_{red} values outside of the confidence interval, two hypothesis can be formulated to explain the result: (a) the function (a constant) chosen to perform the fit is insufficient to represent the data set, therefore, the surface is not uniform; or (b) the uncertainties were estimated incorrectly. Thus, in order to use χ^2_{red} as a criterion for the quality of fit, the uncertainties should be estimated correctly, since an adequate fit means that the agreement between the data and the adjusted function is compatible with the uncertainties associated with the data (Vuolo, 1996).

RESULTS AND DISCUSSION

According to the methodology presented to evaluate the spectral uniformity of the reference surfaces in the flowchart of Figure 3, the first step consisted of analyzing the consistency of the raw data. After this analysis, it was concluded that the data were not biased for either Brazil or Tuz Gölü. Therefore, mean, standard deviation and standard deviation of the mean were determined for each sampling point. Figure 4 shows the mean reflectance factor of the surface first point (Point 1) *versus* wavelength.

After RF values and their repeatability related uncertainties (standard deviation of the means) were determined for each sampling point on the surface, RF behavior was evaluated along the sample points (Fig. 5).

Observing Figures 5a and 5b, together with the other data, it was found that apparently the estimated uncertainties for each point were distinct and varied greatly, particularly for Brazil (Fig. 5a). However, these uncertainties were expected to be statistically the same, since the measurements were performed under repeatability conditions. First, the Cochran test was performed to evaluate the homoscedasticity of the variance for each point, Eq. (2), to determine whether this variation corresponded to a simple statistical fluctuation of the measurements or if the data represented, in fact, different distributions (homoscedastic). For the surface measurements in Brazil, where $n = 4$ and $k = 20$, critical value was 0.2205 (at 5% significance level). On the other hand, for the measurements in Tuz Gölü, where $n = 5$ and $k = 46$, the critical value was 0.0965, also at 5% significance level. Table 1 shows the Cochran test results for the two surfaces, in Brazil and Turkey at six chosen wavelengths, which are the central wavelengths of the spectral bands and the most common in onboard satellite sensors (e.g., Landsat TM).

Table 1 – Cochran test results for the two surfaces, in Brazil and Turkey, for six chosen wavelengths.

Wavelength (nm)	$C_{calculated}$ (Cochran test)	
	Brazil	Tuz Gölü
480	0,1835	0,0972
560	0,2135	0,0852
660	0,2189	0,0813
835	0,2071	0,0754
1650	0,2039	0,0670
2210	0,1620	0,0912

Table 1 shows that the $C_{calculated}$ values of the Cochran test are below the critical value, except for the 480 nm wavelength, in Tuz Gölü. Therefore, according to this criteria, it can be concluded that sample variances can be the same (that is, statistically equal) at a 5% significance level.

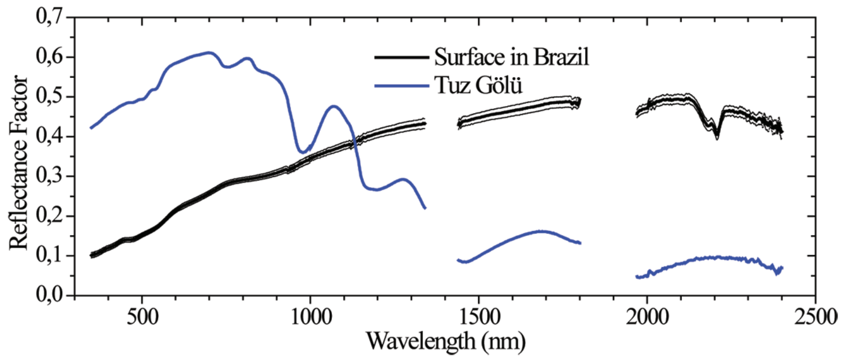

Figure 4 – Plot of mean surface Reflectance Factor (RF) *versus* wavelength for the first point. In black, surface RF for Brazil shows the spectrum variation taking into consideration the given statistical uncertainty (standard deviation of the mean); and in blue the RF for Tuz Gölü, for which the statistical uncertainties (standard deviation of the mean) were small compared to the plot dimension and are not shown. The water absorption (about 1.4 and 1.9μm) and very noisy (wavelengths greater than 2.4μm) regions are not shown.

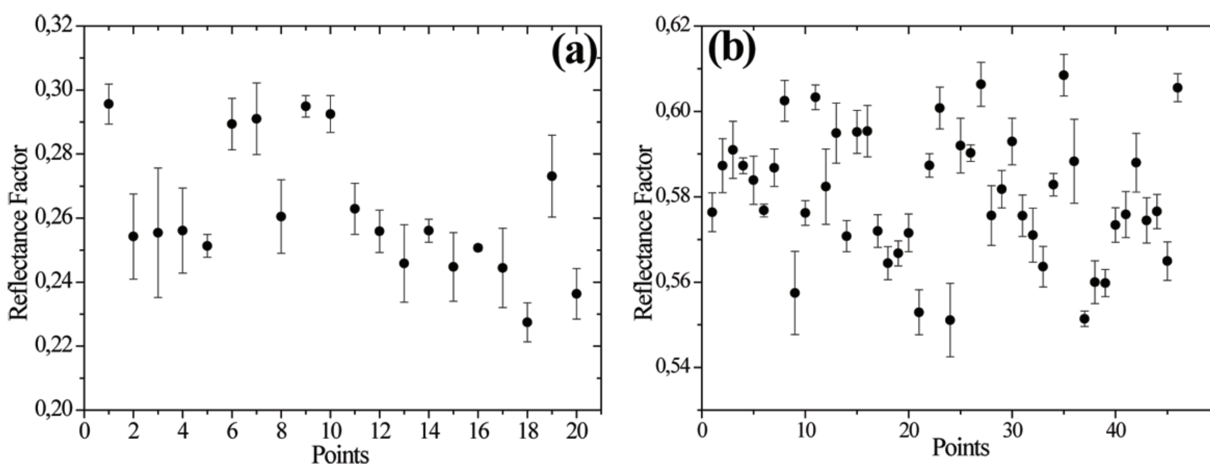

Figure 5 – Surface reflectance factor behavior along the sample points for the 835 nm wavelength. (a) surface RF for Brazil; and (b) RF for Tuz Gölü. It should be noted that the uncertainty bars correspond to the standard deviation of the mean.

In addition to the Cochran test, it was also verified whether the histogram of sample distribution variances fit a chi-square distribution with $k-1$ degrees of freedom, χ^2_{k-1}. Figure 6a shows the probability density function chi-square with 19 degrees of freedom, χ^2_{19}, along with the histogram of sampling distribution variances for the surface in Brazil. Figure 6b shows the same with 45 degrees of freedom for the surface in Tuz Gölü, Turkey.

The histograms of Figure 6, along with other histograms, show that the chi-square distribution does not adequately represent variance behavior at all points. This may indicate, for example, that the variance (and, of course, standard deviation) are statistically different from one point to another. Consequently, their distributions would be different for each point and the reference surface cannot be considered spectrally uniform. However, due to the result of the Cochran test, we decided to assume that the variances obtained for each point of the reference surface were homoscedastic. With this result, global standard deviation, σ_{global}, and the uncertainty of measurement repeatability, $\sigma_{repeatability}$, can be calculated using Eq. (3) and Eq. (4), respectively. Then, the various uncertainties, $\sigma_{various}$, was calculated according to Eq. (5), and finally, final uncertainty, σ_{final}, was given by Eq. (6). The uncertainties estimated to characterize the reference surfaces, regarding: (a) measurement repeatability, $\sigma_{repeatability}$; (b) equipment and procedure repeatability, $\sigma_{various}$; and (c) final uncertainty, σ_{final}, are shown in Figure 7.

Figure 7 shows that uncertainty due to repeatability of the measurements is the main component of the final uncertainty, and it is practically the responsible for the final uncertainty for both

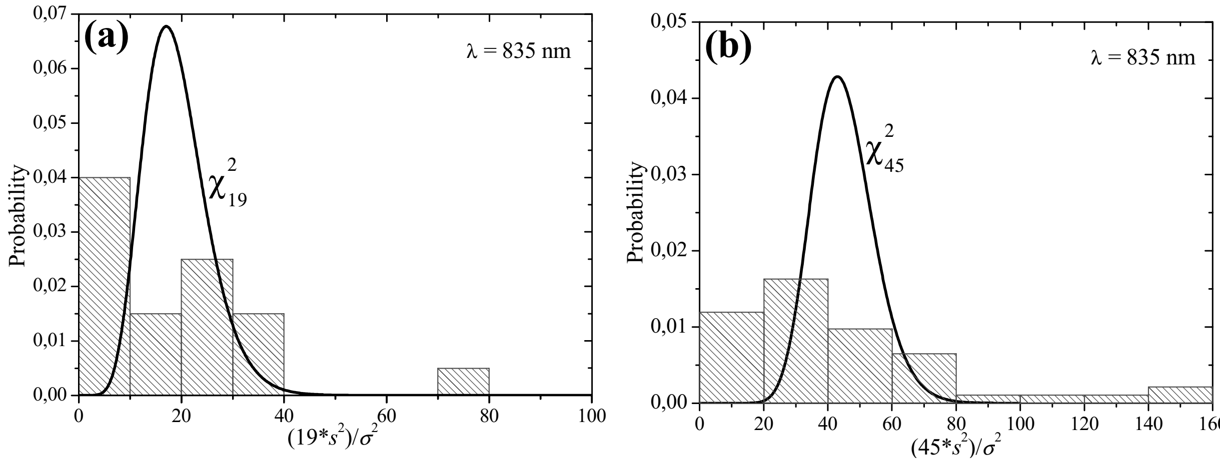

Figure 6 – Histogram of the sampling distribution variances for the 835 nm wavelength, along with the probability density function of the chi-square distribution with 19 and 45 degrees of freedom. (a) surface in Brazil and (b) salt lake Tuz Gölü, in Turkey.

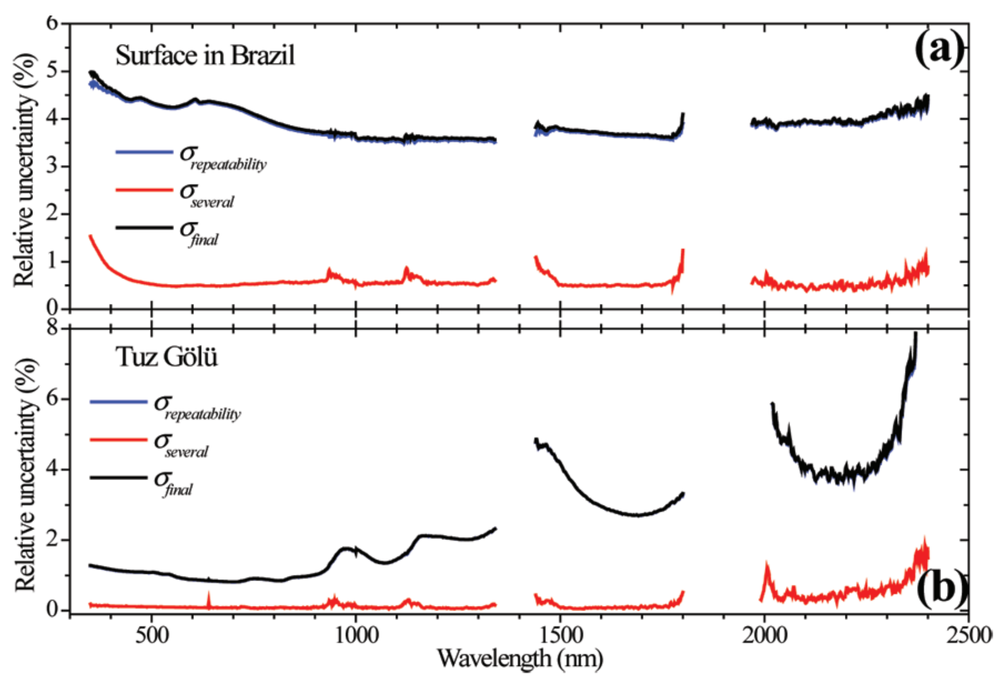

Figure 7 – Plot of the uncertainties estimated for each point on the reference surface as function of wavelength. (a) uncertainties for the measurements in Brazil; (b) uncertainties for the measurements in Tuz Gölü, Turkey.

surfaces, in Tuz Gölü and Brazil. For this reason, the curves for $\sigma_{repeatability}$ are plotted together with σ_{final} for both surfaces. In general, the uncertainty for each point was approximately 4% for the surface in Correntina (Brazil), and varied between 1 and 8% for the salt flat in Tuz Gölü, Turkey.

With the values of surface RF and σ_{final} determined, the correction with respect to the reference plate, corrected RF, was determined by Eq. (7) and its uncertainty by Eq. (8). This new uncertainty for corrected RF remained practically the same as the final uncertainty because the uncertainties of plate calibration were very small: lower than 0.25% (Pinto, 2011) and contributed very little to σ_{final}.

After this procedure, the behavior of RF along the points on the surface was analyzed again. Figure 8 shows the values of corrected RF for each point, with the respective final uncertainty.

Figures 8a and 8b, together with other results, show that the result does not seem biased and neither spatially correlated (i.e., with the measurement sampling points). Therefore, a constant

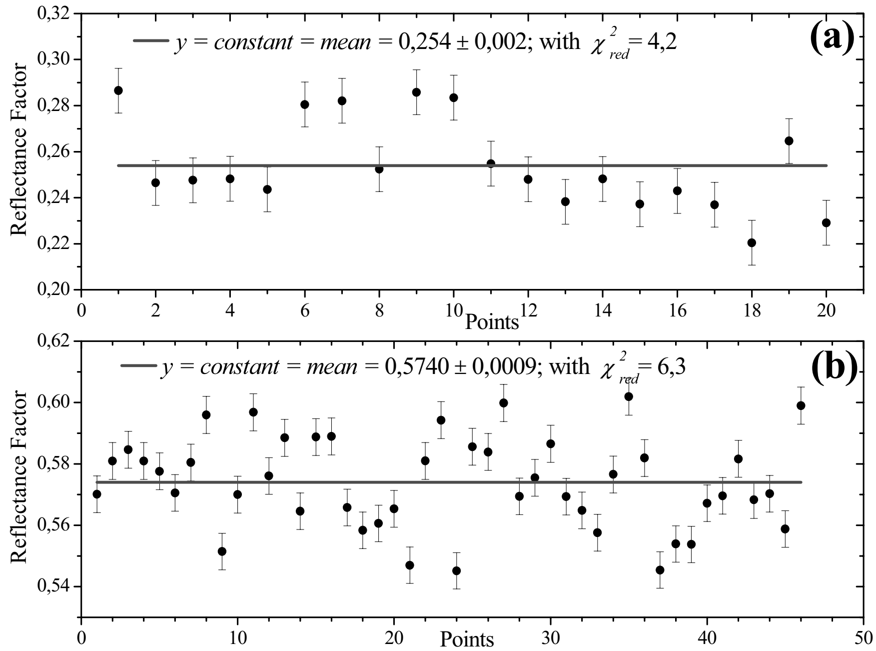

Figure 8 – Behavior of surface RF, for the 835 nm wavelength, along the points. (a) RF of surface in Brazil; and (b) RF in Tuz Gölü. The red line shows the function fitted to the data.

Table 2 – Results for the fit of mean RF, performed with the data collected to evaluate the spectral uniformity of the reference surfaces.

Wavelength (nm)	Fit: Brazil			Fit: Tuz Gölü		
	FR_{Mean}	$\sigma_{relative}$ (%)	χ^2_{red}	FR_{Mean}	$\sigma_{relative}$ (%)	χ^2_{red}
480	0.1132 ± 0.0011	1.0	3.7	0.4805 ± 0.0009	0.19	6.4
560	0.1496 ± 0.0014	0.9	3.9	0.5515 ± 0.0009	0.16	6.4
660	0.1994 ± 0.0019	1.0	4.1	0.5876 ± 0.0009	0.15	5.9
835	0.254 ± 0.002	0.8	4.2	0.5740 ± 0.0009	0.16	6.3
1650	0.429 ± 0.004	0.9	2.3	0.1560 ± 0.0006	0.38	11.9
2210	0.343 ± 0.003	0.9	2.5	0.0916 ± 0.0005	0.55	9.1

function was adjusted to the experimental data, where the constant is the simple mean: $y = constant$. Figure 8 shows the adjustment, and Table 2 shows the result of this fit. Five wavelengths were chosen for this fit, since the behavior is similar for the others.

For the surface measurements in Brazil, with 19 degrees of freedom, the expected χ^2_{red} varies between 0.4 and 1.9, with 98% confidence. For the measurements in Tuz Gölü, with 45 degrees of freedom, the expected χ^2_{red} varies between 0.6 and 1.6, also with 98% confidence. However, Table 2 shows that reduced chi-square, χ^2_{red}, for both surfaces in Brazil and Tuz Gölü, in Turkey, are outside the range of acceptable values and were much higher than 1, thus indicating that: (a) the used function was not the most suitable to represent the data-set; or (b) the uncertainties may have been underestimated.

Firstly, if (b) was true, the uncertainties would be greater than the estimated ones, thus making the adjusted function acceptable and therefore, implying that eventually the surface could be spectrally uniform. However, the estimate of the uncertainties is reliable; since $\sigma_{various}$ carries all Type B uncertainties and the statistical uncertainty is determined by the standard deviation of the means (Type A uncertainty). Thus, the final uncertainty contains all the available information regarding dispersion of the means of RF_{target}. Therefore, this assumption was considered false.

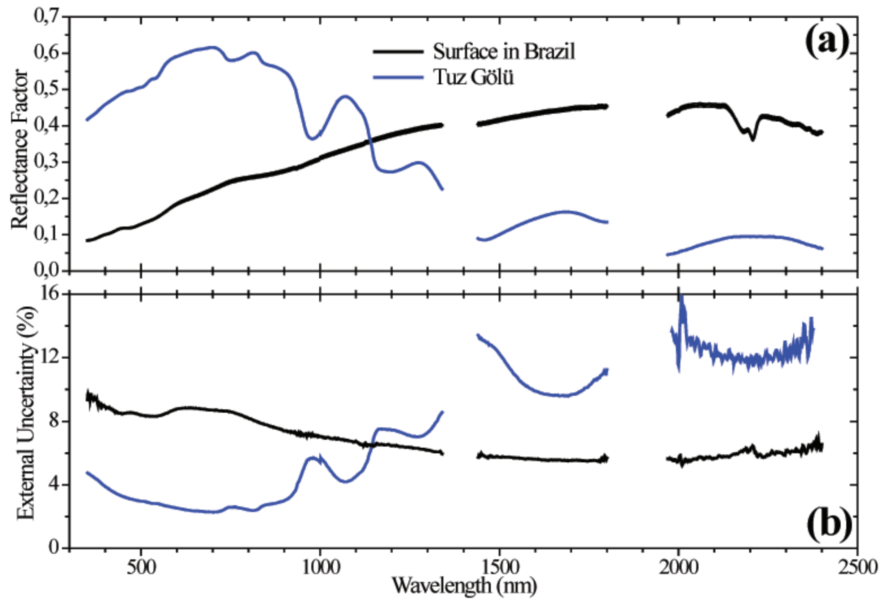

Figure 9 – (a) mean reflectance factor for each point on the reference surface *versus* wavelength; and (b) external uncertainties for each sampling point on the surface *versus* wavelength.

Secondly, in hypothesis (a) the surface would not be uniform, since the chosen function (one mean of the RF means) would be inadequate to represent the entire data set. Thus, a single RF (for a given wavelength) could not represent the RF of the entire surface.

Thus, assuming that the uncertainties have been evaluated properly, it can be concluded that the two studied surfaces are not spectrally uniform, since the mean RF values on the sample points of the reference surface are significantly different. Another fact that corroborates this hypothesis is that the variance histogram could not be represented by the chi-square distribution as shown in Figure 6. As previously mentioned, one of the characteristics for an area to be considered ideal for calibration missions is to be spectrally uniform. However, the non-uniformity issue does not preclude its use for sensor calibration. In the case where the surface is not uniform, a mean reflectance factor cannot be determined for the entire surface, and therefore, a sensor calibration procedure should be performed for each point, when possible (for each sub-area of the surface). Such procedure was performed by Ponzoni et al (2007), who calibrated the sensor TM Landsat 5, using a non-spectrally uniform region of Uyuni Salar.

An important point to be mentioned is that many studies related to the characterization of the reference surface assume that the reference surface is uniform. If the surface is considered uniform *a priori*, the mean of the estimated surface reflectance factors can be calculated for each one the sampling points using data external uncertainty, according to the equation:

$$\sigma_{external} = \sqrt{\left(\frac{1}{k-1}\right) \times \sum_{1}^{k} (x_k - \bar{x})^2} \tag{9}$$

where: k is the number of points; x_k is the mean value of RF of the reference surface at point k; and $\bar{x}$ is the mean RF of the surface k points.

As it can be seen, the procedures and calculations to determine uncertainty associated to external uncertainty, $\sigma_{external}$, and to various uncertainties, $\sigma_{various}$, are similar, see Eq. (5). However, in the case of $\sigma_{various}$ there is no doubt whether the target is uniform, since it is exactly the same surface, the Spectralon reference plate, at all sampling points.

Figure 9a shows the mean RF for the two reference surfaces and Figure 9b the external uncertainties for each point. These figures show that the external uncertainties for each point are larger than the final calculated uncertainties (Fig. 7), and the values vary between 6 and 9% for the surface in Brazil and between 2 and 16% for Tuz Gölü, in Turkey.

CONCLUSIONS

The described methodology was applied to evaluate the spectral uniformity of reference surfaces to be used in the calibration of airborne and orbital electro-optical sensors, and to estimate the uncertainties involved in the process.

Radiometric data were collected at sampling points on two surfaces in Brazil and Turkey to evaluate their spectral uniformity. The final uncertainty obtained for the reflectance of each sampling point was about 4% for the agricultural area in Correntina, Brazil and between 1 and 8% for the salt flat Tuz Gölü, in Turkey.

From the results, it was concluded that the surfaces were not spectrally uniform, since the mean reflectance values of the points on the surface and their variances were significantly different. Nevertheless, the two surfaces can still be used to calibrate sensors. The procedure, then, involves calibrating the sensor for each point (or for each sub-area of the surface) or to use the mean RF of the surface with an external uncertainty.

It is also noteworthy that the spectral uniformity evaluation of these two surfaces was performed at ground level, that is, the measurements were obtained using field spectroradiometer. However, data collection can be done at aircraft or orbital level; therefore, it would be interesting to evaluate surface uniformity at other levels of data collection.

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