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TEMPORAL STABILITY OF TUZ GÖLÜ AND ATACAMA DESERT REFERENCE SURFACES FOR ABSOLUTE CALIBRATION OF ORBITAL SENSORS

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ABSTRACT. The vicarious absolute calibration of electro-optical sensors dedicated to the Earth observation includes the definition of a reference surface from which radiometric measurements taken from the ground are compared to the effective radiance measured by the sensor in orbit. In order to facilitate the surface radiometric characterization process and consequently the sensor radiometric calibration, it is desirable that the surface presents, besides additional characteristics, temporal reflectance stability. This study aimed to evaluate the temporal stability of two potential reference surfaces for radiometric calibration of orbital electro-optical sensors located at: Tuz Gölü Salar in Turkey and Atacama Desert in Chile. Therefore, a temporal analysis of the radiometric properties of these two surfaces using cloud free images of TM/Landsat 5 sensor, acquired from 2003 to 2011, was performed. It was concluded, based on statistical criteria, that both reference surfaces do not presented temporal stability. Nevertheless, both surfaces may still be used for sensor calibration purposes if they were submitted to further spectral characterization with higher frequency and/or if the surfaces were considered stable "enough" within a certain limit of variation in reflectance. Taking that into account, according to the results of this work, it can be stated that Tuz Gölü surface reflectance has temporal stability within a range of 3-14% and the Atacama Desert better than 6%.

Keywords: Earth observation sensors, radiometric calibration, reflectance, TM/Landsat 5.

RESUMO. A primeira etapa para a realização da calibração absoluta de sensores de observação da Terra é a definição de uma superfície de referência. Um dos métodos mais comuns de calibração após o lançamento do sensor utiliza medições radiométricas de áreas localizadas na superfície terrestre. Para facilitar o processo de caracterização da superfície e consequentemente o processo de calibração radiométrica, é desejável que a superfície apresente, entre outras características, estabilidade temporal. Assim, este trabalho teve como objetivo avaliar a estabilidade temporal de duas superfícies de referência potenciais para a calibração radiométrica de sistemas sensores eletro-ópticos: o salar de Tuz Gölü na Turquia e o deserto de Atacama no Chile. Para tanto, foi realizada uma análise temporal do comportamento espectral das duas superfícies por meio de imagens do sensor TM abordo do Landsat 5 livres de nuvens adquiridas nos anos de 2003 a 2011. De acordo com os resultados obtidos foi possível concluir, segundo os critérios estatísticos, que as duas superfícies de referência não apresentam estabilidade temporal. Apesar disso, as duas superfícies ainda podem ser utilizadas para calibração de sensores. Nesse caso, deve-se caracterizar espectralmente as duas áreas com maior frequência e/ou considerar a superfície como sendo "suficientemente" estável se a variação na reflectância ao longo do tempo for menor do que um determinado valor. Se esta consideração for feita pode-se afirmar, segundo o resultado desse trabalho, que Tuz Gölü tem estabilidade temporal entre 3 a 14% e o deserto de Atacama melhor do que 6%.

Palavras-chave: sensores de observação da Terra, calibração radiométrica, reflectância, TM/Landsat 5.

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INTRODUCTION

The conversion of original Digital Numbers (DN) to radiometric quantities such as radiance or reflectance is necessary to the application of orbital remote sensing data in quantitative approaches. This conversion depends on the sensor absolute calibration (Slater et al., 1987; Ponzoni et al., 2007; Helder et al., 2013). One possible alternative for post-launch absolute calibration is the reflectance based method, which depends on the identification of reference surfaces located on the Earth surface. This in-flight calibration alternative is also called as vicarious calibration. In general terms the main goal of the vicarious calibration is to estimate the Top of the Atmosphere (TOA) radiance from a specific surface, which is assumed as effectively measured by the sensor in orbit and compare it to the DN generated by the sensor.

The reference surface selection is based on several characteristics that include spatial and temporal radiometric stability. Scott et al. (1996) and Thome (2001) have presented some ideal characteristics of a reference surface for absolute calibration purposes, which can be divided in two groups: (i) local environmental and geomorphologic conditions (altitude, annual cloud cover levels, wind speed, etc.) and (ii) the surface characteristics, including, the spectral and spatial uniformity, isotropy, temporal uniformity and stability. Considering the long term usage of a specific reference surface, the temporal stability is one of the most important characteristic that has to be evaluated.

The Committee on Earth Observation Satellites (CEOS) has evaluated some reference surfaces around the Earth. One of the most frequently utilized and studied by the CEOS Working Group on Calibration and Validation (CEOS/WGCV) is a salty surface of Tuz Gölü, located in Turkey. The potential of other surfaces has been mentioned, but unfortunately, detailed studies have not been performed in order to confirm their actual potential.

In South America there are some potential surfaces located in Bolivia and in Chile. Lamparelli et al. (2003) and Ponzoni et al. (2004) have explored the Salar de Uyuni salty surface located in Bolivia, to calibrate the TM/Landsat 5 sensor. Although no calibration campaigns have been carried out in Chile, there are some interesting surfaces that could at least be evaluated in the Atacama Desert region.

The objective of the present work was to evaluate the temporal spectral stability in the visible, VIS (400-700 nm), near infrared, NIR (700-1000 nm) and short wave infrared, SWIR (1000-2400 nm) of the electromagnetic spectrum of a specific surfaces located at Tuz Gölü and at Atacama Desert. Additionally the main sources of uncertainty associated to this evaluation are described.

TUZ GÖLÜ AND ATACAMA DESERT

Currently, there are eight official reference surfaces named by CEOS for orbital sensors absolute calibration purposes. The Tuz Gölü (Fig. 1A) is one of them and it is located in Turkey around 910 m above the sea level. During the dry season its surface is covered by salt resulting in high reflectance levels at the visible spectral region (Gürol et al., 2010).

According to Cosnefroy et al. (1996), desert surfaces are good candidates to be evaluated for orbital sensors calibration, especially for those that run on the optical spectral ranges (visible, NIR and SWIR). Therefore, the Atacama Desert (Fig. 1B) presents potential characteristics to be considered as a reference surface. Nevertheless, the Atacama region has not been explored for such purpose.

The Atacama Desert is located in the northern of Chile, around 2000 m above the sea level. The climate is extremely arid, being one of the driest regions in the world. As observed by Betancourt et al. (2000), the Atacama region presents low precipitation levels (around 100 mm per year).

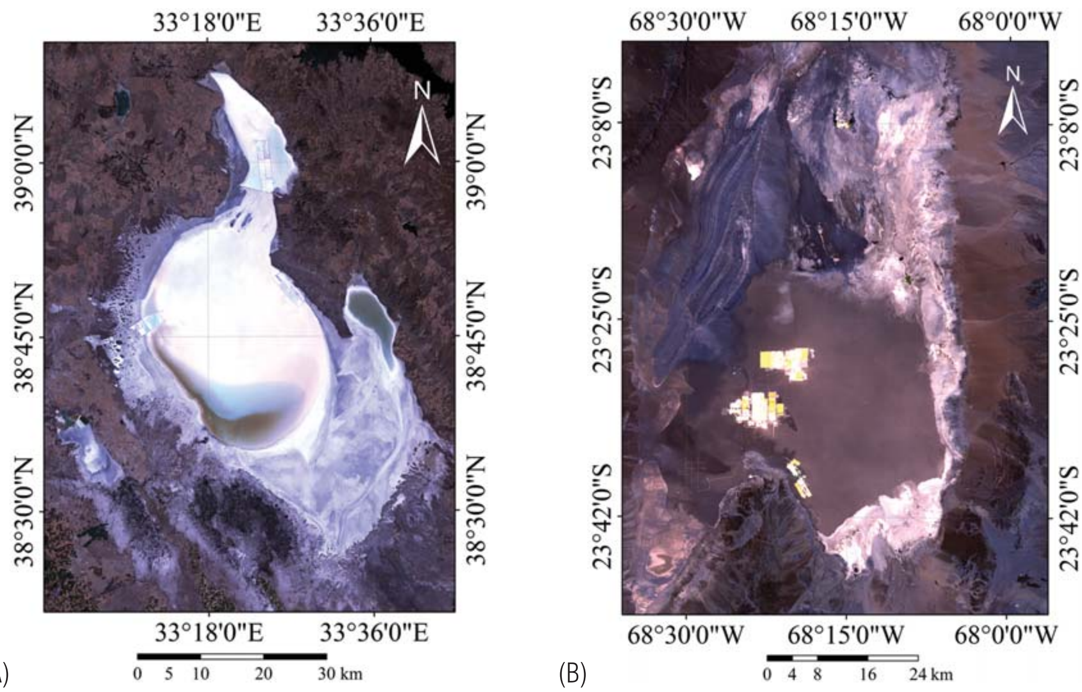
METHODOLOGY

According to Gürol et al. (2010) the best period to perform calibration campaigns in Tuz Gölü is from July to August (summer time in Turkey). Thus, five TM/Landsat 5 scenes (path 177 and row 33) corresponding to this period were obtained (see Table 1). From the Atacama region, seven TM/Landsat 5 images were also obtained (path 233 and row 76), for the corresponding summer period in Chile (November, austral summer) (Table 1). It was chosen only TM/Landsat 5 images from Tuz Gölü and Atacama Desert unaffected by clouds and available at the USGS site (USGS, 2003a).

Note that the assessment has been conducted in the months that are appropriate for the calibration mission, i.e., it has been assessed if surfaces are temporarily stable in the months of July and August in Tuz Gölü and November in Atacama Desert. In addition, both the illumination and viewing geometries of these images are similar (Table 1).

The images products used here, both Tuz Gölü and Atacama Desert, were the Landsat 5 Surface Reflectance data products. Therefore, the images underwent a procedure to correct for the atmospheric effects. In USGS (2013b) and Masek et al. (2006) more information is found about this correction and the conversion of DNs into surface reflectance values.

As the values contained in the images represent physical values with atmospheric correction (surface reflectance) there must be compatibility of radiometric data collected over time. In other



(A) (B)

Figure 1 – (A) Tuz Gölü surface in Turkey and (B) Atacama Desert surface in Chile.

Table 1 – List of TM/Landsat 5 images utilized in this study.

Date	Time (UTC)	Sun Elevation (Degree)	Sun Azimuth (Degree)
Tuz Gölü			
07/14/2003	08h03min	60.80	117.96
07/09/2007	08h21min	64.27	123.18
07/30/2009	08h16min	60.44	126.77
07/17/2010	08h17min	62.74	123.49
08/21/2011	08h16min	55.90	135.07
Atacama Desert			
11/11/2003	14h08min	59.61	85.13
11/29/2004	14h16min	61.15	93.12
11/19/2006	14h25min	63.56	87.55
11/24/2008	14h14min	60.97	91.30
11/27/2009	14h21min	62.44	91.86
11/14/2010	14h20min	62.42	85.41
11/01/2011	14h18min	60.94	77.87

words, it is expected to be possible to compare the reflectance of the surface obtained in different dates within a time series.

Figure 2 presents the flowchart with the steps followed in this work. The procedure includes two main steps: (i) the determination of the mean surface reflectance for each year and (ii) the evaluation of the surface reflectance temporal stability.

Temporal Mean Reflectance

The surface reflectance analysis and associated uncertainties were performed for both surfaces (Tuz Gölü and Atacama) and for temporal set of images and for each TM/Landsat 5 band (bands 1, 2, 3, 4, 5 and 7). So, the mean value of the surface reflectance for each temporal set of image (with their respective associated uncertainty) was determined for Tuz Gölü and Atacama Desert surfaces.

Inside both reference surfaces it was arbitrarily defined a rectangular area of 720 m by 900 m. Inside this rectangular area 10 subareas of 360 m to 180 m were distributed. Figure 3 shows the spatial conception of that surface subdivision. The subarea dimension was determined taking into account the absolute calibration campaigns of orbital sensors with medium spatial resolution such as 10 m to 80 m (Pinto et al., 2012).

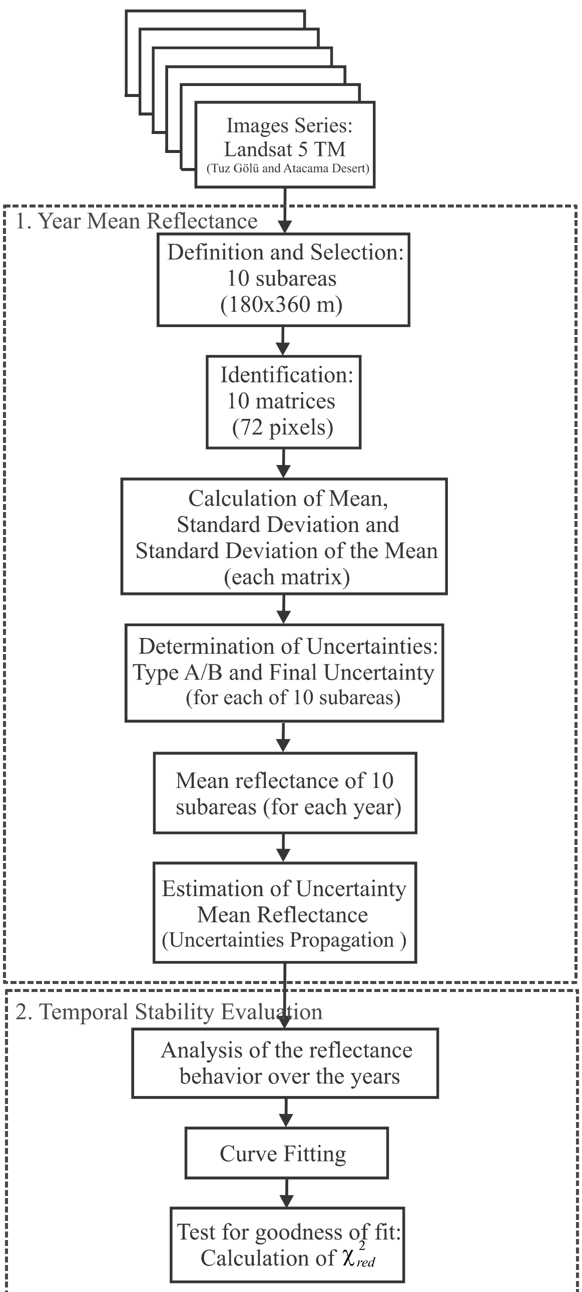


Figure 2 – Methodological steps.

The subarea corresponds to 72 pixels (12 by 6) of TM/Landsat 5 images. From these 12 by 6 pixels it was calculated the mean, the standard deviation and the standard deviation of the mean. This last statistical parameter represents the statistical uncertainty (type A) and it is determined by Eq. (1) (Vuolo, 1996; ABNT, 2003; JCGM, 2008).

$$\sigma_A = \frac{\sigma_P}{\sqrt{N}} \qquad (1)$$

where: σ_p is the sample standard deviation; and N is the observation number, which in this case is 72 pixels.

Besides the statistical uncertainties, there are other sources of uncertainty that may be evaluated by non-statistical procedures (type B). Here it was considered two additional uncertainties sources: (i) the digitalization uncertainty and (ii) additional uncertainties, such as the instrument itself.

Concerning digitalization uncertainty, sensors generate digital numbers as a result of radiance measurement and the reflectance value has a rectangular distribution (ABNT, 2003; JCGM, 2008) which varies between 0 (zero) to 1 (one). In this case the associated uncertainty of the digitalization was estimated according to Eq. (2).

$$\sigma_{\text{digitalization}} = \frac{\left(\frac{\text{reflectance\_range}}{I}\right)}{2 \times \sqrt{3}} = \frac{\left(\frac{1}{254}\right)}{2 \times \sqrt{3}} \qquad (2)$$

where: reflectance_range is the reflectance range from 0-1; and I is the interval number for the digitalization. In this case, TM/Landsat 5 sensor was digitalized in 8 bits, so the digitalization interval is 254.

Each reference surface was admitted spectrally uniform. Thus, the ten subareas should present the same mean surface reflectance values, taking into account the estimated uncertainties. So, it was possible to fit a constant function (mean) to the data set. Once the fitting function is known, it is feasible to estimate uncertainties using the reduced chi-square (χ^2_{red}) (Bevington & Robinson, 2003). Therefore, additional uncertainties were estimated for $\chi^2_{\text{red}} = 1$ (Bevington & Robinson, 2003).

Once the three uncertainties (statistical, digitalization and additional) were estimated, it was possible to estimate the final uncertainty of the mean surface reflectance from each subarea, using Eq. (3):

$$\sigma_\rho = \sqrt{(\sigma_{\text{statistical}})^2 + (\sigma_{\text{digitalization}})^2 + (\sigma_{\text{additional}})^2} \qquad (3)$$

The next step included the estimation of the mean surface reflectance from the ten subareas applying Eq. (4).

$$\overline{\rho}_{\text{year}} = \frac{1}{10} \times \left[\sum_{i=1}^{10} \overline{\rho_i}\right] \qquad (4)$$

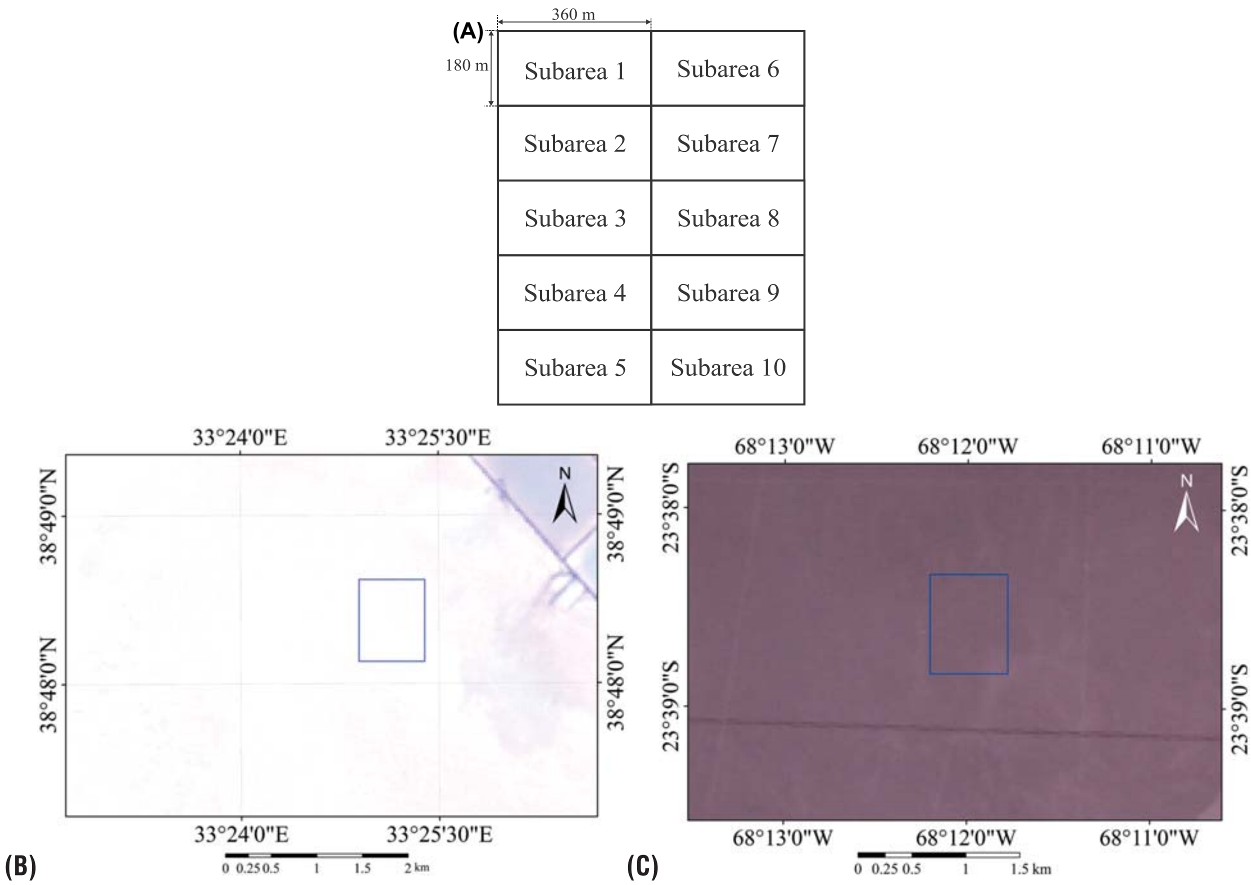


Figure 3 – (A) The spatial localization of the specific area evaluated in (B) the Tuz Gölü and (C) Atacama Desert.

where: $\overline{\rho}_{\text{year}}$ is the mean surface reflectance of the ten subareas, which represents the mean surface reflectance of the entire area at a specific year; and $\overline{\rho_i}$ is the mean surface reflectance from the subarea i.

The uncertainties A and B types were already estimated for each subarea. So, it was estimated the mean uncertainty, which is estimated indirectly, applying the "uncertainty propagation" statistical procedure, described by Eq. (5) (Vuolo, 1996; JCGM, 2008).

$$\begin{aligned}\sigma^2_{\overline{\rho}_{\text{year}}} = {} & \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_1}\right) \times \sigma^2_{\rho_1} + \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_2}\right) \\ & \times \sigma^2_{\rho_2} + \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_3}\right) \times \sigma^2_{\rho_3} + \cdots \\ & + 2 \times \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_1}\right) \times \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_2}\right) \times \sigma^2_{\rho_1\rho_2} + \cdots \\ & + 2 \times \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_1}\right) \times \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_3}\right) \times \sigma^2_{\rho_1\rho_3} + \cdots \\ & + 2 \times \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_2}\right) \times \left(\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_3}\right) \times \sigma^2_{\rho_1\rho_3} + \cdots\end{aligned} \tag{5}$$

where: $\frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_1}, \frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_2}, \frac{\partial\overline{\rho}_{\text{year}}}{\partial\rho_3}, \ldots$ are the dependent on the secondary quantities, $\overline{\rho}_{\text{year}}$, is regarding the primary quantities $\rho_1, \rho_2, \rho_3, \ldots$, respectively (also called sensitivity confidents); $\sigma_{\rho_1}, \sigma_{\rho_2}, \sigma_{\rho_3}, \ldots$ are the uncertainties of the primary quantities $\rho_1, \rho_2, \rho_3, \ldots$, respectively; and $\sigma^2_{\rho1\rho2}, \sigma^2_{\rho1\rho3}, \sigma^2_{\rho2\rho3}, \ldots$, are the covariance, representing the dependencies between the primary quantities.

Covariance may be understood as the common part of the uncertainties of two quantities. In this work, the covariance is due to the Type B uncertainty, both digitalization and additional uncertainties. When the primary quantities are independent, the covariance is zero. However, in the case of this study a significant correlation exists between the primary quantities, hence the covariance cannot be ignored (ABNT, 2003; JCGM, 2008).

Temporal Stability Evaluation

The temporal stability was evaluated by the surface reflectance dynamic, including a new data fitting. To be considered stable through the years, the surface reflectance should have the same mean value (considering the associated uncertainties). So, a reflectance mean value was fitted for the time period considered, and the fitting performance was determined with the dispersion degree between the fitting function and the data set. The reduced chi-square χ^2_{red} was used as a criterion for the evaluation of the dispersion degree (Bevington & Robinson, 2003).

The χ^2 indicates the difference between the fitting function and the experimental data set taking into account the uncertainties calculated. Being $f(x)$ the fitting function of a data set composed by n experimental points $(x_i; y_i, \sigma_i)$, the quantity χ^2 is:

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{y_i - f(x_i)}{\sigma_i} \right)^2 \tag{6}$$

where: y_i is a measurement of y, estimated experimentally when $x = x_i$; σ_i is the uncertainty of y_i; and $f(x_i)$ is the fitting function.

The quantity χ^2 is strongly affected by the number of experimental points (n). Thus, χ^2_{red} seems to be more appropriate as a reference:

$$\chi^2_{\text{red}} = \frac{\chi^2}{v} \tag{7}$$

where: v is the degrees of freedom of the fitting function. If n is the number of experimental points and p is the number of fitting parameters, so $v = n - p$.

Suitable goodness of fitting values are achieved when χ^2_{red} is near to 1. Nevertheless, to perform such evaluation it is necessary to define a confidence interval that is dependent upon the degrees of freedom of the fitting. A more detailed interpretation of χ^2_{red} values can be accessed on Bevington & Robinson (2003).

If χ^2_{red} is according to the acceptable values within a specific significant level, it indicates that the mean reflectance values, from each year, are homogeneous, i.e., the reference surface presents temporal stability. When the χ^2_{red} values are out the confidence interval, there are two possible hypotheses: (i) the fitting function (a constant) is not good enough to represent the data set, thus, the surface does not present temporal stability; or (ii) the uncertainties were estimated incorrectly (some uncertainties or correlation sources were neglected, for example). So, using χ^2_{red} as a fitting evaluation criterion it is necessary to fully estimate the uncertainties, since an appropriate fitting means that the agreement between the experimental data set and the fitting function is compatible to the associated uncertainties (Vuolo, 1996).

RESULTS AND DISCUSSION

The values of surface reflectance from the images in the blue band (452 518 nm) were saturated for the surface of the Tuz Gölü (in Turkey). Thus, it was not possible to perform data processing for this band. As described above, the mean reflectance values, the standard deviation and the mean standard deviation of the subareas were determined. The relative statistical uncertainties (standard deviation of the mean) estimated for the Tuz Gölü surface, were around 0.1% for bands 2, 3 and 4 (green, red and near infrared). In bands 5 and 7 (short wave infrared) the statistical uncertainties were lower than 0.7%. From the Atacama surface the relative statistical uncertainties were lower than 0.2% for all spectral bands. The next step included the estimation of the digitalization uncertainty according to Eq. (2).

The additional uncertainties were determined considering $\chi^2_{\text{red}} = 1$. The relative additional uncertainties for the Tuz Gölü were lower than 1.5% in the bands 2, 3 and 4. In bands 5 and 7 they were lower than 6.5%. For the Atacama surface the relative additional uncertainties varied from 0.3 to 2.5%. Once these three uncertainties were calculated (statistical, digitalization and additional) it was estimated the final uncertainty associated to the mean surface reflectance from each one of the ten subareas, according to Eq. (3). The mean surface reflectance for each one of the ten subareas and the fitting function are shown in Figure 4.

So it was calculated the annual mean surface reflectance using Eq. (4). To calculate the uncertainty associated to this value it was used Eq. (5). The mean surface reflectance values for each year and for each TM/Landsat 5 spectral band including the associated uncertainties is presents in Table 2.

Considering the Tuz Gölü surface it is possible to compare the results presented on Table 2 to those described by Pinto et al. (2012) and Pinto et al. (2013). The authors showed a reflectance spectral curve generated from radiometric measurements carried out during a field campaign (using a spectroradiometer) that was consistent with the reflectance values generated here, presenting a great statistical similarity.

The surface temporal stability evaluation was performed considering the mean surface reflectance variation during a specific period of time (Table 2) for each TM/Landsat 5 spectral band. Figure 5 presents the mean surface reflectance at each year of the temporal data set for band 4, as well as its respective final uncertainty (1σ). The results for the other bands were all similar (thus not shown herein).

Finally the constant function was fitted using the surface reflectance mean correspondent to the entire period of the data set (from 2003 to 2011). Figure 5 shows the fitting function, for which the quality was evaluated using the χ^2_{red} value (see Eq. (7)) taking into account the associated uncertainties. Table 3 shows the results of such evaluation for each TM/Landsat 5 spectral band.

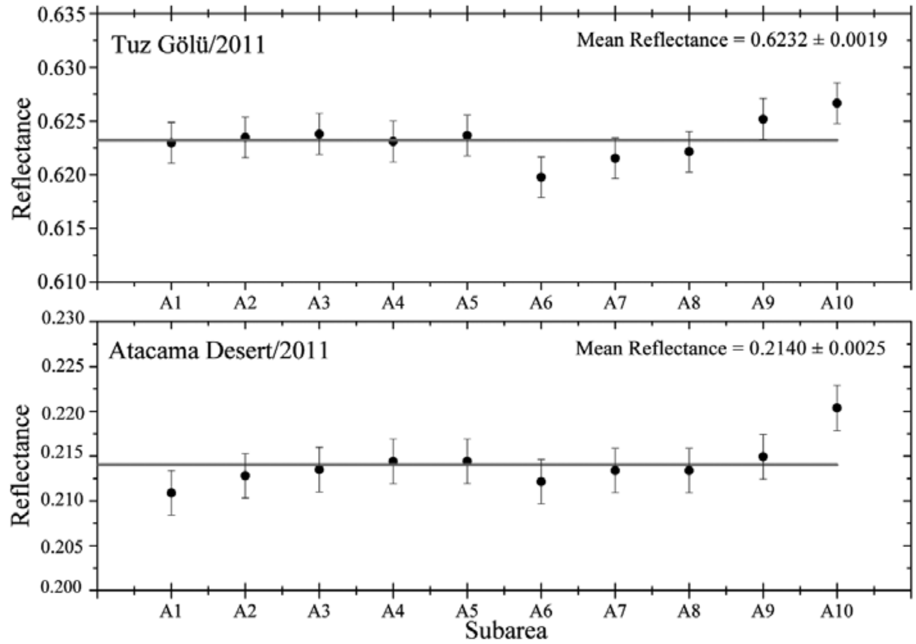


Figure 4 – Surface reflectance as a function of each of the ten subareas in 2011 for the band 2 TM/Landsat 5 sensor. The uncertainty bars are the final uncertainties (1σ) calculated using Eq. (3). In the line is the fitting function (mean reflectance of year).

Table 2 – Mean surface reflectance at each year for the TM/Landsat 5 spectral bands with their respective uncertainties.

Tuz Gölü						
Year	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
2003	#	0.5538±0.0013	0.6126±0.0011	0.5994±0.0023	0.130±0.004	0.0819±0.0030
2007	#	0.577±0.005	0.606±0.003	0.594±0.007	0.110±0.007	0.075±0.003
2009	#	0.5966±0.0018	0.6426±0.0017	0.614±0.007	0.120±0.004	0.0742±0.0029
2010	#	0.580±0.007	0.620±0.006	0.570±0.004	0.088±0.004	0.0601±0.0024
2011	#	0.6232±0.0019	0.6724±0.0021	0.615±0.008	0.120±0.005	0.0763±0.0026
Atacama Desert						
Year	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
2003	0.1944±0.0017	0.2431±0.0017	0.2930±0.0019	0.3296±0.0022	0.3527±0.0020	0.3263±0.0016
2004	0.1705±0.0017	0.2202±0.0016	0.2713±0.0020	0.3115±0.0021	0.3261±0.0022	0.3213±0.0017
2006	0.1695±0.0014	0.2196±0.0016	0.2704±0.0021	0.3142±0.0023	0.3289±0.0021	0.3264±0.0019
2008	0.183±0.005	0.242±0.005	0.290±0.006	0.331±0.006	0.344±0.006	0.349±0.005
2009	0.171±0.004	0.224±0.004	0.274±0.005	0.318±0.005	0.335±0.006	0.330±0.005
2010	0.1654±0.0026	0.212±0.003	0.267±0.004	0.312±0.004	0.344±0.004	0.328±0.004
2011	0.1701±0.0021	0.2140±0.0025	0.2668±0.0027	0.315±0.003	0.325±0.003	0.3252±0.0026

For the Tuz Gölü surface the degree of freedom was 4 (four). So, the expected χ^2_{red} value should be from 0.1 to 3.3 at 98% of confidence level (Vuolo, 1996). For the Atacama surface the expected χ^2_{red} value should be around 0.15 to 2.8 at 98% of confidence level, since the degrees of freedom were 6 (six). According Table 3 data, χ^2_{red} values were calculated out from the acceptable range of values, and they were higher than 1 (from the Tuz Gölü and Atacama surfaces), considering the standard uncertainty (1σ). This result indicates that, as previously mentioned: (i) the function used was not the most appropriate to represent the data set or (ii) the uncertainties may have been underestimated (not considered all uncertainty sources).

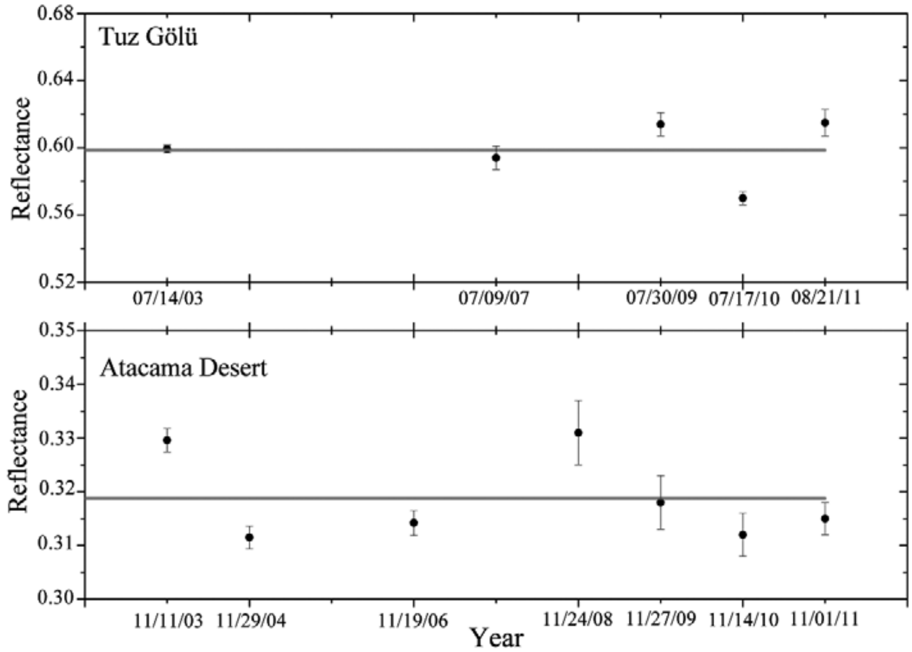


Figure 5 – Surface reflectance variation through the years for spectral band 4 TM/Landsat 5 sensor. In the line it is possible to see the fitting function.

Table 3 – Fitting results of mean reflectance over the years to assess the temporal surface stability Tuz Gölü and Atacama Desert.

Band	Tuz Gölü		Atacama Desert	
	ρ_{Mean}	χ^2_{red}	ρ_{Mean}	χ^2_{red}
1	#	#	0.175	29
2	0.586	259	0.225	31
3	0.631	210	0.276	19
4	0.598	15	0.319	8
5	0.114	16	0.337	20
7	0.074	10	0.329	8

First, if case (ii) would be true, the uncertainty would be greater than the estimated by making the set function acceptable, which would thus imply that, eventually, the surface could provide temporal stability. However, we have good confidence in the estimation of the uncertainties, since the final uncertainty contains all the "information" available. Considering case (i) the surface would not be stable over time, because the function (mean reflectance values) would not be adequate to represent the entire data set. Thus a single reflectance value for a wavelength cannot represent the surface reflectance over the years.

Hence, assuming that all uncertainties have been properly evaluated, it can be concluded that both the Tuz Gölü and Atacama surfaces do not exhibit temporal stability for the spectral bands analyzed, i.e., there are significant differences between the mean values of the temporal surface reflectance that are not explained by the uncertainties.

The non-uniformity of any reference surface does not preclude its use for sensor calibration purposes. In this case, even the surfaces do not present time stability, it is possible to spectrally characterize them with higher frequency. In addition, it is absolutely impossible that any surface presents the entire list of "ideal" absolute calibration characteristics. The Tuz Gölü is, for instance, a good example of that since it has been considered an official reference surface by CEOS and our results have shown that it is not stable over time.

Thus, the most important aspect when choosing a surface for calibration is acquiring knowledge about their main characteristics, especially those that can affect significantly the calibration process of Earth observation sensor systems.

Finally, it was noted that the variations found in this study regarding the reflectance value over time (2003 to 2011) can be considered low, i.e., surfaces may be considered "enough" sta-

Table 4 – Coefficient of variation (CV) of the surface reflectance from 2003 to 2011.

Band	Tuz Gölü			Atacama Desert		
	ρ_{Mean}	Standard Deviation	CV(%)	ρ_{Mean}	Standard Deviation	CV(%)
1	#	#	#	0.175	0.010	5.8
2	0.586	0.026	4.4	0.225	0.013	5.6
3	0.631	0.027	4.4	0.276	0.011	3.9
4	0.598	0.018	3.1	0.319	0.008	2.6
5	0.114	0.016	14.1	0.337	0.011	3.2
7	0.074	0.008	11.0	0.329	0.009	2.7

Table 5 – Temporal coefficient of variation (CV) of four surfaces used in the sensors calibration. In column marked "sensor" represents the sensor used to assess the surface temporal stability.

Surface	CV(%)	Sensor	Authors
Railroad Valley Playa	1 to 4	AVHRR	Bannari et al. (2004)
La Crau	10 to 15	ASTR	Rondeaux et al. (1998)
Dunhuang	3	MODIS	Hu et al. (2010)
Saharan and Arabian Deserts	1 to 2	METEOSAT	Cosnefroy et al. (1996)

ble over time. Some authors, like Kneubühler et al. (2005) and Bannari et al. (2005) consider a homogenous surface when the temporal coefficient of variation (CV), defined as the ratio between the standard deviation and the mean, is less than 3%. Table 4 presents the CVs of all bands of the TM/Landsat 5 sensor obtained for the two studied areas.

As can be noted in Table 4, the results indicate that the temporal CV between 2003 and 2011 in the Tuz Gölü range from 3-14% and the Atacama Desert CV was less than 6% in all bands. The Tuz Gölü can be considered as having temporal stability performance from 3 to 14% and Atacama Desert better than 6%.

For comparison purposes Table 5 shows the temporal CV of four (4) surfaces used for sensor calibration: (a) Railroad Valley Playa in U.S; (b) La Crau in France; (c) Dunhuang in southwest China; and (d) Saharan and Arabian Deserts in North Africa and Saudi Arabia. The first three areas are considered official calibration sites by CEOS.

To assess the temporal surface stability images of the TM sensor aboard Landsat 5 from 2003 to 2011 were analyzed. The final uncertainties obtained for the mean reflectance of each year, varied from 0.2 to 6.5% for the Tuz Gölü lake and ranged from 0.5 to 2.7% for the Atacama Desert.

According to the achieved results, Tuz Gölü and the Atacama Desert surface do not have temporal stability for the analyzed spectral bands. This is because there are significant differences between the mean surface reflectance values over the years (between 2003 and 2011) that could not be explained by the estimated uncertainties. Nevertheless, the two surfaces may still be used for sensor calibration purposes. In this case, the two areas should be spectrally characterized more frequently and/or consider the surface as being "enough" stable within a certain limit of maximum variation in the reflectance values over time. If this consideration is made, it is possible to assert, according to the results of this study, that the Tuz Gölü performance has temporal stability between 3-14% and the Atacama Desert from 2.6-5.8%.

CONCLUSION

We described and applied a methodology for evaluating the temporal stability of two potential areas for radiometric calibration of sensors: (a) the Tuz Gölü, a salt lake in Turkey, and (b) the Atacama Desert in Chile. Moreover, we also estimated the major uncertainties involved in this process.

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