Potential of Getis Statistics to Characterize the Radiometric Uniformity and Stability of Test Sites Used for the Calibration of Earth Observation Sensors

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***Abstract*—The calibration of airborne and satellite remote sensing sensors is a fundamental step for the rigorous validation of products derived from satellite data. Because of the inaccessibility of Earth Observation Satellites on orbit, the direct calibration method based on a test site with ground reference data is often considered necessary. However, the problem of radiometric spatial uniformity and temporal stability of test sites constitutes an important issue in the accuracy achieved in calibration operations and the long-term characterization of satellite sensor radiometry. Generally, the coefficient of variation and semivariograms are the most widely used tools for evaluating the radiometric uniformity and stability of a calibration site. In this study, we analyze for the first time the potential of Getis statistics compared to the coefficient of variation for the study of the radiometric spatial uniformity and temporal stability of the Lunar Lake Playa, Nevada (LLPN) test site. The results obtained show the potential and the importance of the synergy generated by these two methods for analyzing the radiometric temporal stability of the LLPN site. Getis statistics provide an excellent spatial analysis of the site while the coefficient of variation provides complementary information on the temporal evolution of the site.**

***Index Terms*—Coefficient of variation (CV), Getis statistics, Lunar Lake Playa, Nevada (LLPN), optical sensor, radiometric calibration, test sites.**

I. Introduction

DURING the last three decades, the demand for remote sensing products has increased tremendously, particularly for the management of natural resources and more generally for environmental. Moreover, the surveillance of the Earth's environment at the local, regional, continental, or global scales using various sensors requires adequate radiometric calibration in order to have accurate and reproducible geophysical and biophysical surveys through time [4]. Consequently, significant errors can spread through all subsequent image processing operations, including spatial and multitemporal analyses, thematic classifications, and the generation of vegetation indexes [15], [18], [29], [36], [42]. To get the maximum from satellite and airborne data-derived products, sensors must constantly be calibrated, the data validated, and the stability and quality of data ensured [3], [42].

The radiometric performances of Earth Observation Satellite sensors change between calibration in the laboratory before launch and on orbit operations [9], [35], [21], [24]. The spectral response characteristics of sensor bandpasses, mirror surfaces, and optical elements can also change postlaunch and over the lifetime of the mission [11], [21], [37]. Therefore, it is normal to view with suspicion any postlaunch change in the relative and absolute sensor calibration parameters and to question the quality of any onboard calibration systems (lamps, solar sensors, etc.). With or without change, spectral response characteristics are an important consideration in radiometric cross-calibration between sensors [38], [40].

In general, the calibration of instruments dedicated to Earth observation is not an easy task. To increase the accuracy of this operation, it is advisable to use several independent methods [9]. Different methods have been used for the relative and absolute calibration of optical sensors: calibration in laboratory before launch in a well-controlled environment; onboard calibration using a lamp, a sphere, a solar diffusion panel, or a solar sensor; calibration through lunar observation; calibration using ground sites with simultaneous ground reference data; calibration using pseudoinvariant features on the ground without independent reference data, interinstrument, and interband calibration [16], [19], [20], [35], [42], [44]. Because of the inaccessibility of the satellite on orbit, the vicarious calibration method based on a ground site using simultaneous ground reference data is often considered an essential step to ensure the best "accuracy versus investment" compromise [16], [35]. The method has the advantage of reproducing the real conditions of image data acquisition. Its accuracy depends closely on the radiometric stability of the calibration site, site reflectance measurements, and knowledge of the atmospheric parameters at the time of image acquisition. In the best conditions of site and measurement stability, it ensures a calibration accuracy in the range of $\pm 2\%$ to $\pm 3\%$ [9], [46], [47]. It should also be noted that these operations concern the space agencies or the organizations responsible for the dissemination of the remote sensing data

Manuscript received October 11, 2004; revised April 20, 2005. This work was supported by the Natural Sciences and Engineering Research Council of Canada.

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Digital Object Identifier 10.1109/TGRS.2005.857913

and not those of the users of the images for thematic mapping, extraction of biophysical, and geophysical parameters, etc.

Calibration sites are never chosen randomly, and to be adequate they must satisfy a certain number of criteria [21], [31], [34], [35], [42]. The most popular sites include the alkali flats of the gypsum desert at White Sands, NM [35], the La Crau site in southern France [16], [30], and the Railroad Valley Playa and Lunar Lake Playa sites in central Nevada [31], [33], [43]. Recently, new sites have been investigated, such as the Newell County Rangeland site in Alberta, Canada [26], [39], [42], the Dunhuang site in Gansu province in China [52], the Tinga Tingana site in the Strzelecki desert in south Australia [23], and the Uyuni Salt Flats site in Bolivia [27]. Other sites such as the Sonora site in northwest Mexico [51], the desert sites of North Africa, and the Arabian Peninsula have also been used for sensor calibration operations [5]–[7] but with little or no ground-based measurements. These cases provide considerable cost savings but require that the temporal stability of the test sites be well characterized and well understood.

The issues of radiometric spatial uniformity and temporal stability of test sites are very important for the calibration and long-term radiometric control of satellite sensor data. The optical properties of any given test site can vary due to different factors such as site surface moisture variations, the presence of lichens and pebbles of different sizes, the presence of vegetation causing spectral variations, variations in the topography generating shade effects, the drying of the surface that leads to small cracks and fissures that trap light, the non-Lambertian character of the surface increasing bidirectional reflectance effects, as well as variable atmospheric conditions [12], [21], [22], [25], [31], [35], [42], [47], [50].

Although the analysis of the spatial uniformity and temporal stability of test site radiometry is fundamental, investigations of this issue are rare. In this study, we carried out such an analysis for the Lunar Lake Playa, Nevada (LLPN) site, which has been used for the calibration of satellite sensors with medium to high spatial resolution. Generally, the coefficient of variation and semivariograms are the most widely used tools for evaluating the radiometric spatial uniformity of a calibration site. In this study, we analyze for the first time the potential of Getis statistics for the study of test site uniformity. Toward this objective, Getis statistics and the coefficient of variation were programmed as a function of different window sizes varying from 3 × 3 to 9 × 9 30-m pixels. Three Systeme Pour l'Observation de la Terre High Resolution Visible (SPOT HRV) multispectral images acquired over the LLPN test site in 1997 and 1998 were used.

II. Materials and Methods

A. Getis Statistics

Spatial autocorrelation can be defined as the degree of dependence between the values of the same variable "X" associated with locations "j" close to each other [8]. The measurement of this parameter requires taking into consideration both its location and the data attributed to it [14]. In the case of image processing in remote sensing, the "j" locations are pixel coordinates, and the attributed data "X" are the digital counts (DC)

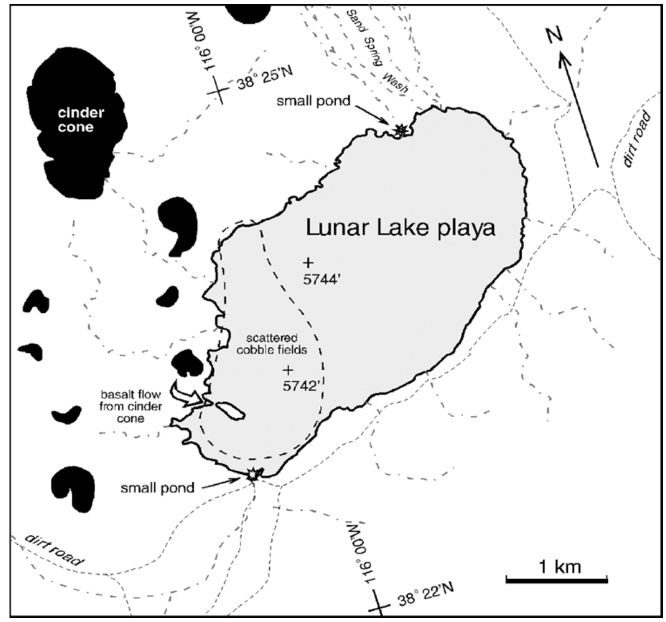

Fig. 1. Map of the immediate area of the Lunar Lake Playa site, Nevada.

or the reflectance [53]. Remote sensing image products portray landscapes in regularly spaced grids with cells of the same size, i.e., pixels [10]. It can be expected that pixels from similar land covers will generate clusters in image feature space that differ in intensity compared to pixel clusters from other land cover types. This clustering translates into a positive spatial autocorrelation when we have a cluster of similar DCs (or the reflectances) and a negative autocorrelation when we have a cluster of dissimilar values [8].

Spatial autocorrelation can be measured by using global or local statistics. Global indicators provide one single measurement summarizing all the spatial interrelations of the entire study area. The reliability of this measure can be reduced if the nature and the extent of the spatial autocorrelation vary significantly over the image. The *local indicators of spatial association* (LISA) were developed by Anselin [2] to find the discrete spatial regimes that are undetectable using global indicators [53]. LISA values are a measure of the extent and nature of the concentration of DCs (or the reflectances) for a limited area within the entire study area [55]. Among these local indicators, there are the Getis statistics that come in two versions [13], [28]. The first version, denoted G_i, excludes the digital count attributed to the pixel "i" from the local sum while this value is included in the second version, denoted G_i^*. Recently, Wulder and Boots [54] have shown that these statistics can be applied successfully to the digital analysis of Landsat Thematic Mapper images acquired over a forest cover presenting a mixture of different species. The potential of the method was clearly demonstrated for extracting information concerning the spatial structure of the forest cover and locating the different species. Moreover, by exploiting Getis statistics and image data acquired by the Special Sensor Microwave/Imager (SSM/I) sensor over snow-covered prairies, Derksen *et al.* [8] identified the dominant configurations of the clusters and their influence of the latter on atmospheric circulation.

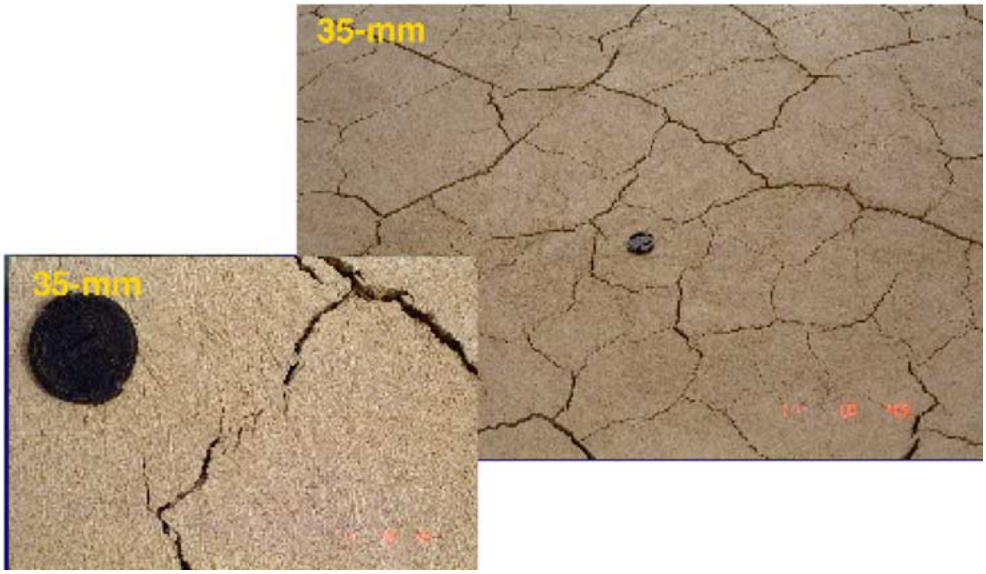

Fig. 2. Photograph showing the surface of the Lunar Lake Playa calibration site in Nevada, the drying of the surface that transforms the landscape into patches of various sizes with fissures that trap light. The camera lens indicates the scale of the photographs.

Getis statistics are defined as follows [28]:

$$G_i^*(d) = \frac{\sum_j w_{ij}(d)x_j - W_i^*\overline{x}}{s\left[\frac{W_i^*(n-W_i^*)}{(n-1)}\right]^{1/2}}. \quad (1)$$

The matrix of spectral weights $\{w_{ij}(d)\}$ is both binary and symmetric with a weight equal to unity ($w_{ij} = 1$) for all the pixels found within distance "d" of pixel "i" considered and a weight equal to zero ($w_{ij} = 0$) for all the pixels found outside "d." $\Sigma w_{ij}(d)x_j$ is the sum of the varying values "X" (DC or the reflectance in the case of images) within distance "d" of pixel "i" (i included), W_i^* is the number of pixels within the distance "d" (i included)

$$W_i^* = \sum_j w_{ij}(d) \quad (2)$$

$$\overline{x} = \frac{\sum_j x_j}{n} \quad (3)$$

$$s^2 = \frac{\sum_j x_j^2}{(n - \overline{x}^2)}. \quad (4)$$

In the above equations, "n" is the total number of pixels, "$\overline{x}$" is the global mean of x, and "s" is the variance of x. In (1), a cluster of pixels with higher than average digital counts yields mostly positive G_i^* values, while a cluster of pixels with lower than average digital counts yields mostly negative G_i^* values [55]. In the case of our study, G_i^* statistics were used for the first time for the characterization of remote sensing radiometric calibration sites. They enabled us to analyze the spatial uniformity of the LLPN site, e.g., to select spatially heterogeneous or homogeneous subareas. Toward this objective, G_i^* statistics and the coefficient of variation were calculated as a function of different window sizes varying from 3 × 3 to 9 × 9 30-m pixels. The resulting images permit the visualization and analysis of homogeneous and heterogeneous pixel clusters.

B. Coefficient of Variation

Knowledge of the relative variation is indispensable for evaluating site radiometric uniformity. Among the tools often used to measure relative dispersal is the coefficient of variation (CV) [17], [41], [44]. It is defined by the ratio of the standard deviation (σ) over the average ($\overline{x}$). The CV was used to characterize the radiometric spatial uniformity and the temporal evolution of the La Crau site in France by Gu *et al.* [17] using SPOT HRV images. The authors set a 20 × 20 pixel window (an area of 400 × 400 m in the middle of the La Crau site), and they moved the window with a sampling step of one pixel on each of the raw images in order to derive images of the coefficient of variation. According to the authors, this method permitted the determination of the most spatially homogeneous area at the La Crau site with a coefficient of variation of 2%. Moreover, Teillet *et al.* [41] calculated the coefficient of variation using SPOT HRV images acquired over the sites of Railroad Valley Playa, NV (U.S.), and Newell County Rangeland, Alberta (Canada), using a variable window size ranging from 3 km × 3 km to 20 km × 20 km with a sampling step of 1 km. The results obtained showed that the most homogeneous areas have a coefficient of variation of 2.5% and 3% respectively for the two sites. Based on the results of the research work previously cited, in the framework of this study we will consider a site homogeneous when the coefficient of variation is 3% or less.

C. Study Site: Lunar Lake Playa, Nevada

The LLPN test site is located approximately 300 miles north of Las Vegas and 100 miles east of Tonopah in central Nevada (38° 23′ N and 115° 59′ W) at an altitude of 1750 m (Fig. 1). The site area is approximately 2 km × 4.5 km and very flat with the terrain elevation varying no more than 1 to 2 m across the site. The climate is continental with a high ratio of clear days and is characterized by important variations in terms of mean precipitation [43]. The central portion of the site (0.5 km × 0.5 km) presents a smooth and homogeneous surface characterized by a

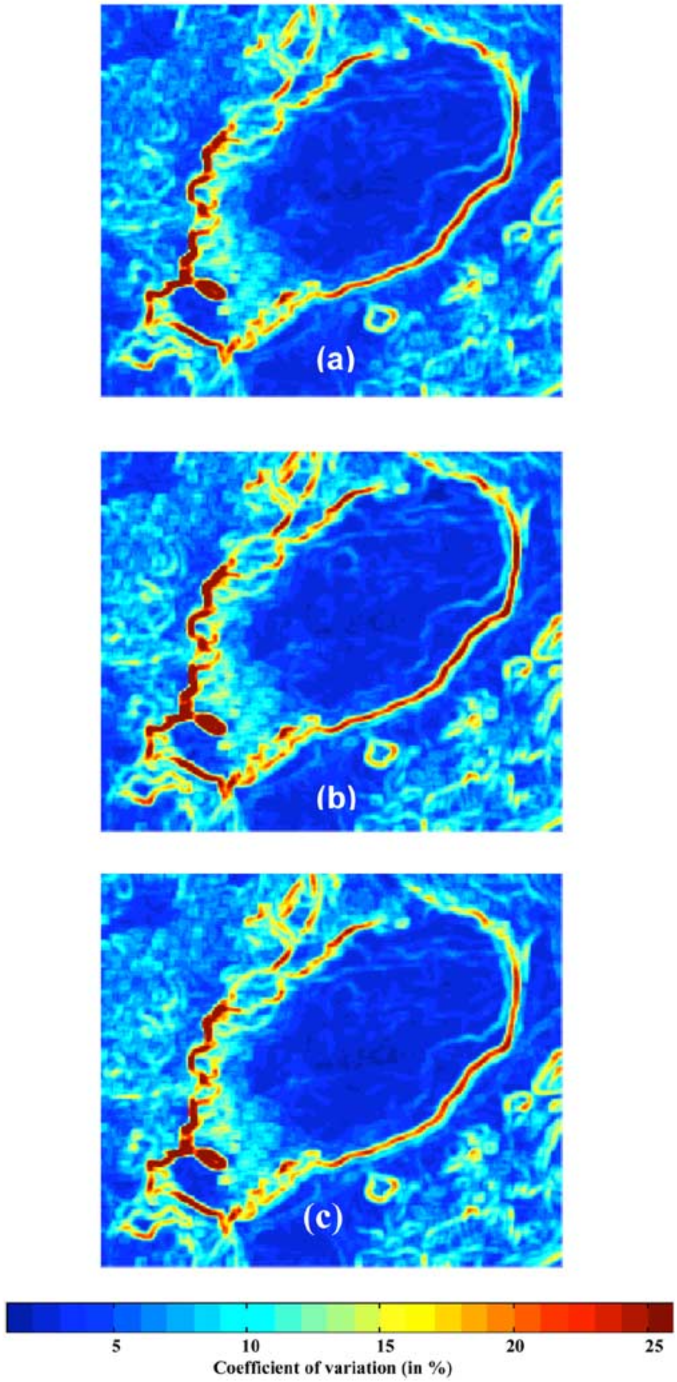

Fig. 3. Images of the coefficient of variation calculated using a 5 × 5 pixel window in the three bands [HRV1 (a), HRV2 (b) and HRV3 (c)] of a SPOT-1 HRV image acquired over Lunar Lake Playa on 10 March 1997.

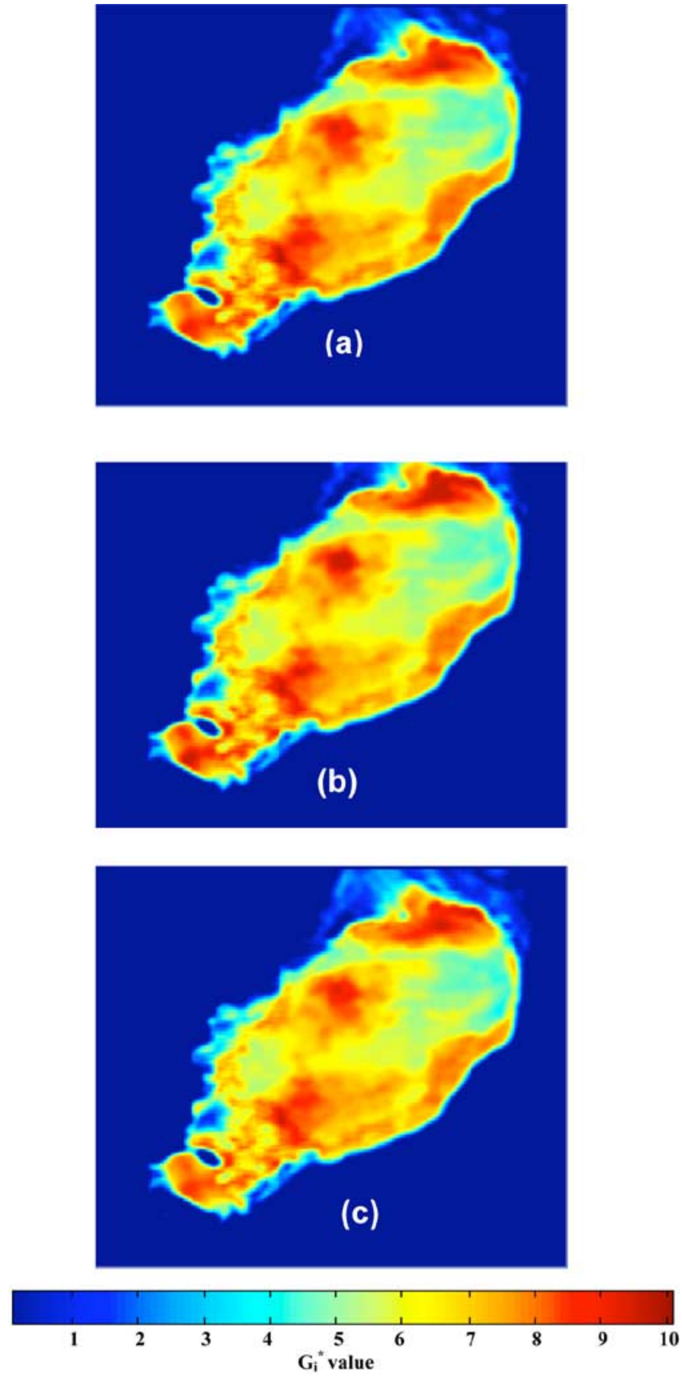

Fig. 4. Images of the Getis statistics calculated using a 5 × 5 pixel window in the three bands [HRV1: (a), HRV2: (b) and HRV2: (c)] of a SPOT-HRV image acquired over the Lunar Lake Playa on 10 March 1997.

good spatial uniformity [31], [33] (Fig. 2). Unfortunately, these characteristics are transitory because of the temporal variations affecting the region. After significant rain or snowfall, the surface of the LLPN can become inundated, modifying the characteristics of the surface while it dries. These transformations can be accentuated further by the high wind in these regions [43].

The soil structure at LLPN is made up of compact lacustrine deposits rich in clay forming a surface composed of units varying in size from 20–30 cm in diameter in the south of the playa and from 10–20 cm in the north. The mineral composition of the site consists of approximately 90% smectites, kaolinites, and vermiculites, and less than 10% carbonates, quartz, feldspath, and micas [32], [33]. According to Vane *et al.* [41], [48] this site is quite satisfactory for the calibration of SPOT and Landsat sensors and by extension more recent high spatial resolution sensors such as the Terra Multi-angle Imaging Spectroradiometer [1], as well as Ikonos, SPOT High Resolution Stereoscopic, QuickBird, etc. Unfortunately, because of its limited area, it cannot be used with reliability for low spatial resolution satellite sensors whose pixel sizes approach a significant fraction of the size of the site.

D. Image Data

The characterization of test site radiometric uniformity through time and space requires image data acquired over a period of many years including different spatial and spectral resolutions and well distributed on a yearly scale or at least on a scale of the period when the site is usable. However, the objective of the study reported in this paper was mainly focused on the potential of Getis statistics and its synergy with the CV for analyzing radiometric uniformity and stability. Hence, among the images archived by the Canada Centre for Remote Sensing (CCRS) and the University of Arizona, Tucson, three cloud-free SPOT HRV images were selected, thus representing limited temporal coverage. These images were acquired on June 18 1998, June 28 1997, and March 10 1997, and they were corrected radiometrically and atmospherically using Second Simulation of the Satellite Signal in the Solar Spectrum (6S) radiative transfer code [49]. The study utilized HRV spectral bands 1, 2, and 3, whose wavelength ranges are 500–590 nm (green), 610–680 nm (red), and 790–890 nm (near-infrared), respectively. These bands are hereafter referred to as HRV1, HRV2, and HRV3.

III. Analysis and Results

In order to characterize the variability of the radiometric spatial homogeneity of the LLPN, we retained a medium size window (5×5 30-m pixels) for all the data processing. This window size offers us a good compromise between a small and a large window. A small window size indicates that spatial dependency is confined to a very localized region while a large distance value indicates more spatially extensive spatial dependence.

Fig. 3 illustrates the results obtained using an HRV image acquired in March 1997. The CVs are very similar for the three bands of the HRV sensor. Also, the highest CVs are recorded on the north and southwest side of the playa, with values between 15% and 25%. This high variation in the CV values indicates the area of LLPN is not really homogeneous and spatial uniformity is low. The lowest CVs are recorded in the middle of the playa, with values on the order of 2% to 4% for the three bands. This low variation indicates good site spatial homogeneity. Also, the low CVs in the near-infrared show that the site is free from vegetation [Fig. 3(c)]. These findings indicate that the surface of the playa is more uniform in the middle of the site. The playa is also known to be bright from the literature [32] and from unpublished measurements made at LLPN (R.P. Gauthier, personal communication), with surface reflectances at visible and near-infrared wavelengths in the range of 0.4 to 0.5, well above the 0.3 recommended by Thome [45] for radiometric calibration test sites. The presence of basalt pebbles dispersed at the southern end of the site possibly explains the high CVs in that area.

Fig. 4 presents an example of the results obtained with Getis statistics derived from HRV data (image acquired in March 1997). The images of this figure show that Getis statistics are nearly identical in all three spectral bands. This figure reveals

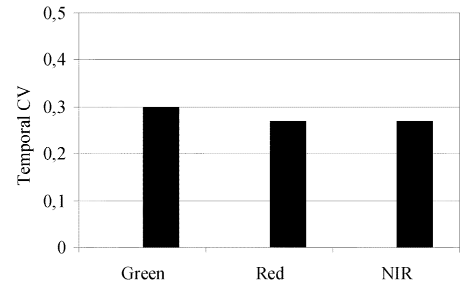

Fig. 5. Temporal evolution of the three HRV bands acquired over the Lunar Lake Playa for the month of June with reference to the month of March 1997.

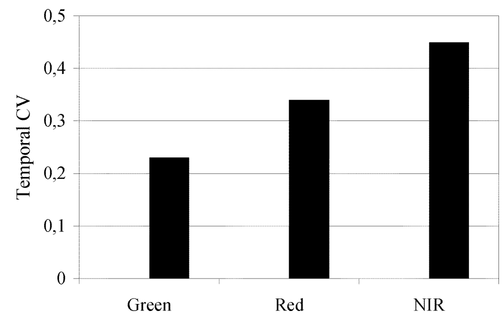

Fig. 6. Temporal evolution of the three HRV bands acquired over the Lunar Lake *Playa* for the month of June 1998 with reference to the month of June 1997.

the spatial heterogeneities and homogeneities in different places of the LLPN site. One can clearly distinguish many clusters of pixels of varying intensities in the three bands. Accordingly, the north and the southwest areas of the site are characterized by high G_i^* values, between 6 and 10, (high brightness: yellow and red color in the images), which means a good spatial uniformity in these area. As to the north end of the playa, the values of G_i^* are smaller (3 to 5; blue-green and yellow in the images), which means a low spatial uniformity in this area. The main factor responsible for this behavior is likely soil moisture variation since March is the wettest month in that area and water is known from direct observation to collect at that end of the playa, which is very slightly lower in terrain elevation (the monthly average rainfall is the highest in March at 33 mm and the lowest is in June at 6 mm).[1]

In general, CV has extracted the borders of the playa and the perimeters of the areas where there is a strong and significant spatial variation. This method shows that the Lunar Lake playa is a homogeneous and relatively uniform site and the heterogeneous zones of the site remain undetectable. On the other hand, the Getis statistics amplify the spatial dependence among pixels and show a good sensitivity to surface conditions, which can be variable in this area and provide an excellent spatial analysis of the site. However, the two methods have shown themselves to be relatively insensitive to spectral variation, insofar as the three broad spectral bands of SPOT HRV are a measure of the spectral dimension.

For the multitemporal characterization of the LLPN site, we calculated the coefficient of temporal variation for the site, on the one hand between the months of March and June of the same year (1997) and, on the other hand, for the month of June in

[1]Based on NCDC cooperative stations in the area (www.worldclimate.com).

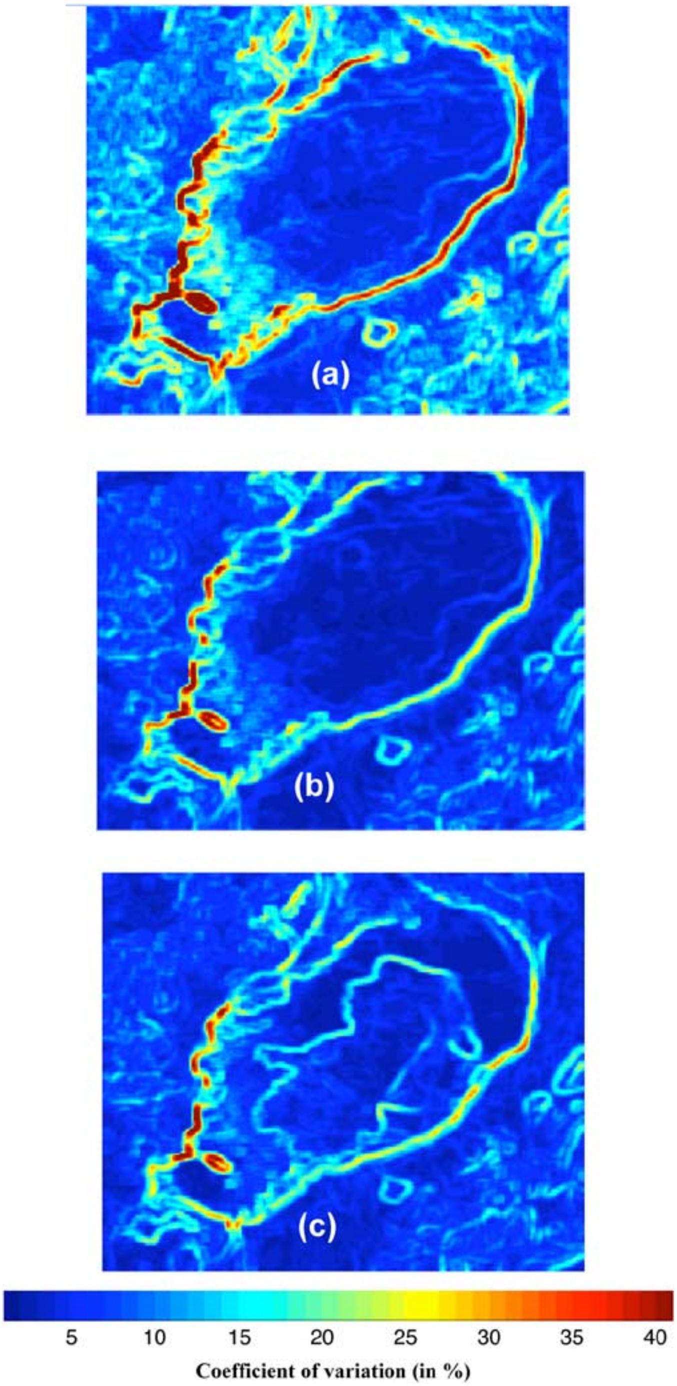

Fig. 7. Images of the coefficients of variation calculated using a 5 × 5 pixel window in the HRV red band (HRV2): (a) March 1997, (b) June 1997, and (c) June 1998.

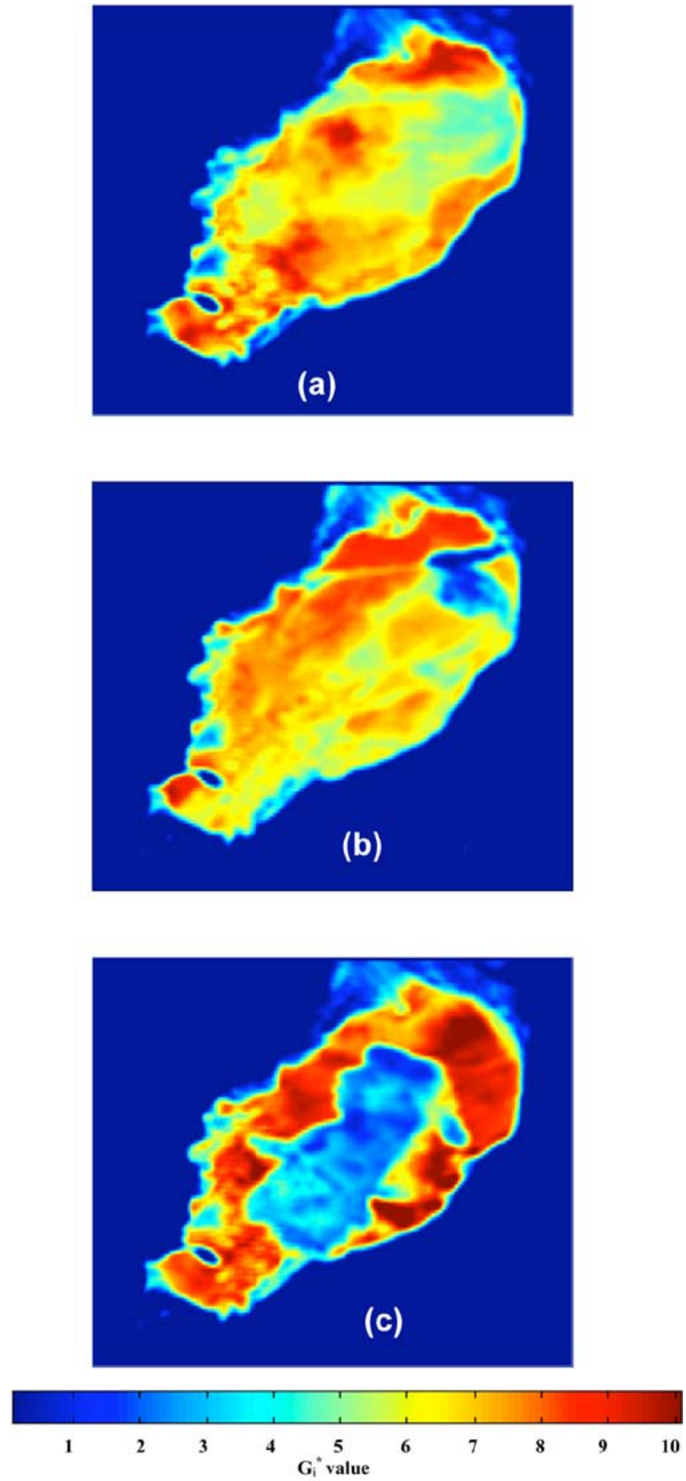

Fig. 8. Images of the Getis statistics using a 5 × 5 pixel window in the HRV red band (HRV2): (a) March 1997, (b) June 1997, and (c) June 1998.

two different years (1997 and 1998). Figs. 5 and 6 indicate how the site surface reflectance has changed over these periods in the three SPOT HRV bands. According to these figures, the CV variation in the three bands is high, on the order of 30% in HRV1, and 27% in HRV2 and HRV3. These results indicate that the LLPN site undergoes changes to its surface. It is thought that these changes are caused by variations in soil moisture resulting from meteorological conditions that can be quite variable in the region, but this hypothesis has not been validated. Figs. 5 and 6 also indicate that this site has undergone a more significant variation, from approximately 22% in the first band to more than 42% in the third band.

To better characterize the temporal variation of the LLPN site, Figs. 7 and 8 present images of the coefficient of variation and of the Getis statistics derived from HRV2. It must be noted that the site behavior in the green and near-infrared bands is the same as in the red band. According to Fig. 7, CV has extracted only the borders of the playa and the perimeters of the areas where there is a significant spatial variation. However, CV also indicates that the site may have generally remained homogeneous between the months of March and June in 1997. According to Fig. 8, Getis statistics extracted spatially homogeneous and heterogeneous areas located in different places of the site. Overall, the images show the areas having undergone the most significant temporal variations. In 1997, the east and west of the playa, possibly affected by moisture in March, became relatively bright and dry in June [yellow to red in Fig. 8(a) and (b)]. However, the southeast region, very bright (red) and uniform in March, has become less homogeneous in June. Moreover, comparison between the two images of the Getis statistics [Fig. 8(a) and (b)] clearly shows that the central portion of the playa has undergone an important change in June 1998 compared to the same period in 1997. Fig. 8(c) shows that the region may be subject to high surface moisture, perhaps generated by the presence of standing water resulting from a rainstorm before the image acquisition date. The surroundings of this affected area show a cluster of high G_i^* values indicating a dry and bright surface during this period.

Based on these results, it is clear that the LLPN site is subject to significant temporal variations, not only in terms of brightness but also in terms of spatial homogeneity. Moreover, using ERS-1 synthetic aperture radar data, Teillet *et al.* [43] noted that the Lunar Lake Playa surface might be subject to temporal variations due to wetting and drying. One can also add the possibility of the redistribution of surface components generated by frequent winds in the region. Even if surface moisture is a transitory phenomenon depending both on the intensity of evaporation and soil hydrodynamic properties (capacity of the soil for diffusing its moisture), its effect should be taken into consideration when using this site for calibration operations.

IV. Conclusion

As we have discussed in this paper, the sites used for calibration operations must meet a number of criteria, including the uniformity and stability of the site's radiometric properties in space and time, respectively. For studying this issue, we developed a methodology based on two types of statistics: the coefficient of variation, a classical tool already used in previous work, and Getis statistics that we used for the first time for the radiometric characterization of a remote sensing radiometric calibration site, the LLPN site in particular. The results for SPOT HRV imagery demonstrated the synergy generated by using the two methods. Getis statistics provide an excellent spatial analysis of the test site independently of the spectral band used. They have shown good potential for the extraction of radiometric heterogeneities for a surface that appears to be homogeneous according to a widely used image-processing tool, the coefficient of variation. On the other hand, while the coefficient of variation does not adequately characterize the site spatially, it provides complementary information on the temporal evolution of the site. The synergy between the two methods provided information on the radiometric uniformity and stability of the site. We have shown that in spite of its apparent spatial homogeneity and its high brightness, the surface of the LLPN site experiences temporal variations presumably controlled by meteorological effects that cause changes in the surface structure (presence of water, moisture variations, and lichen forming).

Acknowledgment

The authors would like to thank the Canada Centre for Remote Sensing and the University of Arizona for the image data and atmospheric and radiometric calibration parameters.

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