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Original paper

The Recognition of the Remnants of the Royal Road of the Interior Land Using High-Resolution Multispectral Satellite Images

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Resumen

Los españoles construyeron el Camino Real de Tierra Adentro en los tiempos de la colonia de México. Tal camino corría entre la Ciudad de México y Santa Fe, en Nuevo México, USA. Algunos remanentes aun sobreviven en México, pero su localización, longitud y condición no son bien conocidas. Por medio de trabajo de campo y de una investigación de los registros dejados por los españoles, se identificaron tres segmentos del Camino Real. Se adquirieron tres imágenes multiespectrales de alta resolución del satélite Pleiades. Tales imágenes cubren tres zonas donde fueron identificados los segmentos del Camino Real y se llevó a cabo un trabajo de campo. Debido a la degradación, los segmentos del Camino Real muestran bajo contraste con respecto al entorno pero una textura distintiva. Se aplicó un procedimiento de realce y agudizamiento a las imágenes con base al operador Vectorial Laplaciano y al análisis de componentes principales (ACP). Tal procedimiento realza la textura y los bordes de los segmentos del Camino Real. Un compuesto RGB falso color formado por el operador Laplaciano, la primera componente principal y la banda 4, produjo una imagen donde los segmentos del Camino Real son claramente observados. Por medio de trabajo de campo se identificaron las coordenadas y las condiciones de los segmentos del Camino Real.

Palabras clave: Camino Real, Arqueología, sensores remotos, procesamiento de imágenes.

Abstract

The Spaniards built the Royal Road of the Interior Land in the colonial times of Mexico. Such a road ranged between Mexico City and Santa Fe, New Mexico, USA. Some remnants still survive in Mexico, but their geographic location, position, length and condition are not well known. By means of fieldwork and a search of historic records left by the Spaniards, three segments of the Royal Road were identified. Three high-resolution multispectral images from the Pleiades satellite were acquired. Such images cover three zones where the Royal Road segments were located, and fieldwork was carried out. Due to degradation, the segments of the Royal Road show a low contrast with respect to the surroundings but a distinctive texture. A procedure of enhancement and sharpening was applied to the images based on the Vector Laplacian operator and Principal Component Analysis (PCA). Such a procedure enhances the texture and the edges of the Royal Road segments. An RGB false color composite formed by the Laplacian operator, the first principal component, and band 4, produced an image where the Royal Road segments are clearly observed. By means of fieldwork, the geographic coordinates and condition of the Royal Road segments were identified.

Keywords: Royal Road, Archaeology, Remote Sensing, Image Processing.

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Introduction

The Royal Road of the Interior Land ranged from Mexico City to Santa Fe, New Mexico, USA. Such a road was a rugged trail and, in some segments, a dangerous route running close to 3,000 kilometers in length. This road was in service for close to three centuries, from 1598 to 1882. In that time, the Royal Road was used for the transit of settlers, to transport goods and information, crops, livestock, and crafts, to several provinces of greater Mexico.

After independence from Spain in 1821, the northern frontier of Mexico was opened up to foreign trade. A new trail from Missouri to Santa Fe was constructed. The City of Santa Fe, New Mexico, quickly became the destination for a steady stream of traders carrying goods. For the next 60 years, the Royal Road, linked to the Santa Fe Trail, became an essential communication path between the growing economies of the United States and Mexico.

The detailed accounts of the expeditionary Juan de Oñate to Santa Fe set the foundations for the determination of the path of the Royal Road (Moorhead, 1995). The city of Santa Fe became the destination of a supply caravan that traversed a journey of 3,000 kilometers that iniciated in Mexico City. The Camino Real was the main trail that supported the displacement of the caravan.

By means of the Royal Road, the foundation of haciendas, bridges, forts and presidios, to protect roads and religious missions, was undertaken. Some segments of the Royal Road were paved, and are associated with churches, missions, farms and bridges. Nevertheless, it should be noted, that much of this heritage has been destroyed by the passage of time and by human intervention. Currently, all prospecting work is based on the registration of traces of some original sections.

In 1972 the Federal Law on Monuments and Archeological Sites, Artistic and Historic, promulgated a law that set an important ground for the identification and preservation of the Royal Road of the Interior Land (Diario Oficial, 1972; Gómez Arriola (eds.), 2012; Comer and Harrower, 2013).

Remote sensing techniques have been used to identify archaeological features. A number of publications account for the research done in archaeology using remote sensing techniques (Staski, 1998; Wiseman and El-Baz (eds.), 2007; Parcak, 2009; Tapete and Cigna, 2016; Hanson and Oltean, 2013).

Jackson (2006) provides a detailed description of the remnants of the Royal Road in New Mexico. Apparently, the Royal Road shows a better preservation in New Mexico than in Mexico. Such a description continues south of the border from El Paso del Norte (Ciudad Juarez) until Mexico City. The description includes the features associated to the Royal Road such as churches chapels, bridges and haciendas.

Preston and co-workers (1998) provide a detailed and colorful account of the exploration of the Royal Road. Preston and co-workers traversed the Royal Road by foot and by horse and provided a beautiful description of the landscapes they encountered.

In this research, it was assumed that the remnants of the Royal Road are observable in high-resolution satellite images and detectable by the use of enhancement and sharpening procedures (Lira and Rodríguez, 2014). A set of high-resolution multispectral images of central Mexico were acquired from the Pleiades Satellite. Efforts were concentrated on the existence of reported tracks in central Mexico, and fieldwork was carried out to confirm the findings of the Royal Road, derived by means of the processing of the high-resolution images.

The objectives of the present research are (i) To show that remote sensing techniques, applied to high-resolution multispectral satellite images, are able to identify segments of the

Royal Road, (ii) to stress the importance of having reliable techniques to help the preservation of this important cultural heritage, (iii) and to identify the actual aspect and level of degradation of such segments. To fulfill the objectives of this research, three tasks were developed. The enhancement of the edges of the Royal Road segments by means of the Principal Component Analysis. In addition, the enhancement of the texture of the segments by means of the Vector Laplacian. The third task was the fieldwork to assess the state of preservation of the segments of the Royal Road.

MATERIALS AND METHODS

1 MATERIALS

The set of high-resolution images cover three segments of the path of the Royal Road in the State of Aguascalientes and the State of Zacatecas (Moorhead, 1995; Gomez Arriola, 2012; Jackson, 2006; Preston, *et al.*, 1998). Basic technical details of the images are provided in Table 1. By means of fieldwork, information on the known tracks of the Royal Road with geographic coordinates were also acquired (Table 2). A SPOT 6 multispectral image was used to define the three study areas of the Royal Road segments. An RGB false color composite was prepared to show the areas of study where geographic features are identified (Figure 1a, 1b, 1c).

Several satellite platforms acquire high-resolution multispectral images of the Earth surface such as Orbview, GeoEye and Pleiades among others. An analytical task was developed to determine a suitable pixel size required to produce a clear identification of the segments of the Royal Road. The task indicated that a pixel of 30 - 50 cm was needed. Then a thorough search was carried out for images of such a pixel size with cloud-free view. The images of the Pleiades sensor were the only available for the three sites selected in this research.

The high-resolution images from the Pleiades 1A, B Satellite carry a pixel of 1.5 x 1.5 m2 in multispectral mode and a pixel of 0.5 x 0.5 m2 in panchromatic mode (Table 1). The Pleiades images were purchased from Earth Observing System ((@CNES (2017)), Distribution Airbus DS).

2 METHODS

2.2 ENHANCEMENT AND SHARPENING

A selected set of high-resolution images was considered for the recognition of the Royal Road. The criterion for such selection was to consider the images that cover a portion of the Royal Road whose existence in central Mexico is known with certainty. Another criterion was to acquire cloud-free images (Table 1). However, the knowledge about the tracks of the Royal Road is a guess; the exact geographical location of such tracks is not well known. The actual condition of the Royal Road was evaluated by visual inspection of published photos (Jackson, 2006; Moorhead, 1995; Preston *et al.*, 1998; Gómez Arriola (eds.), 2012).

A fusion of the multispectral image with the panchromatic image was applied in a procedure known as pan sharpening. The pan sharpening process produced a multispectral image with a pixel of 0.5×0.5 m^2 (Table 1). The pan sharpening procedure generates a multispectral image with a pixel the size of the panchromatic band. In addition, this procedure preserves the spectral response of the scene enabling further analysis of the multispectral image.

The width of the known segments of the Royal Road is between 3 -10 meters. The contrast between the Royal Road and its surroundings is low. However, the texture of the Royal Road is noticeably different from the adjacent field. The Vector Laplacian operator (Lira and Rodriguez, 2014) was applied to the resulting image generated by the pan sharpening procedure to enhance the texture of the Royal Road. The Principal Component Analysis (PCA) was applied to such images to enhance the edges of the Royal Road. The Laplacian and the first principal component produced images such that the enhancement and definition of the edges of the Royal Road segments were achieved. Therefore, the Royal Road segments were identifiable in the enhanced images. Details of the Laplacian, the PCA and the spectral response of soil and vegetation can be found in Lira (2010; 2011). A block diagram shows the rationale of the enhancement and sharpening process (Figure 2). An RGB false color composite with the Laplacian, the first principal component, and the band 4 was prepared (Figures 3, 5, 7). In this RGB, the Laplacian enhances the texture of the road, the first principal component enhances the edges of the road and band 4 enables the difference between soil and vegetation. The next two sections provide details on the Laplacian and the principal component analysis.

2.3 Vector Laplacian

Let **f**(**r**) be a vector valued function that describes a multispectral image formed by η-bands. The vector **f**(**r**) = {b1(*x,y*), b2(*x,y*), . . . b*η*(*x,y*)} represents the value of a pixel through the bands, i.e., the image value at a pixel location **r** = (*x,y*). The function **f**(**r**) is a vector field that describes the multispectral image.

The Fourier transform of **f**(**r**) is defined as (Bracewell, 2003; Ebling and Scheuermann, 2005; Lira, 2010)

$$\mathbf{F}(\boldsymbol{\omega}) = \mathrm{F}\,[\mathbf{f}(\mathbf{r})] = \int_{-\infty}^{+\infty} \dots \int_{-\infty}^{+\infty} \mathbf{f}(\mathbf{r}) \exp\{-2\pi \mathrm{j}\mathbf{r} \cdot \boldsymbol{\omega}\} \mathrm{d}\mathbf{r} \qquad (1)$$

The Fourier transform of the vector field **f**(**r**) produces a vector valued function in Fourier space, namely, $\mathbf{F}(\boldsymbol{\omega}) = \mathscr{F}[\mathbf{f}(\mathbf{r})]$. The vector $\mathbf{F}(\boldsymbol{\omega})$ = {F1(ω1, ω2),… F2(ω1, ω2), Fη (ω1, ω2)}, represents the spatial frequency content of the image at the location ω = (ω1, ω2). In $\mathbb{R}^{\eta}$,the coordinates in the Fourier domain (ω1, ω2), and spatial domain (*x,y*), cover the same range, 1 ≤ (*x*, ω1) ≤ M and 1 ≤ (*y*, ω2) ≤ _N, but their meaning is different: (*x,y*) represents spatial coordinates, while (ω1, ω2) represents spatial frequencies.

In discrete space $\mathbb{Z}^{\eta}$, the coordinates in the Fourier domain **k** = (k_1, k_2), and spatial domain **q** = (m,n), cover the same range, 1 ≤ (m, k1) ≤ M and 1 ≤ (n, k2) ≤ N. If **f**(**q**) ∈ , $\mathbb{Z}^{\eta}$ where (m,n*;* k_1, k_2) ∈ ℤ, then the discrete version of equation (1) is

$$\mathbf{F}(\boldsymbol{k}) = \mathrm{F}\,[\mathbf{f}(\mathbf{q})] = \sum_{i}^{\eta} \dots \sum_{m}^{N} \mathbf{f}(\mathbf{q}) \exp\{-2\pi \mathrm{j}\mathbf{q} \cdot \mathbf{k}\} \qquad (2)$$

where **f**(**q**) = {b_1(*x,y*), b_2(*x,y*), . . . bη(*x,y*)} and **F**(**k**) = {F_1(k_1,k_2), F_2(k_1,k_2), . . . Fη (k_1,k_2)}. The Laplacian in $\mathbb{Z}^{\eta}$ of the vector field **f**(**q**) is therefore

$$\mathrm{F}\,[\nabla^2 \mathbf{f}(\mathbf{q})] = -(2\pi)^2 |\mathbf{k}|^2 \,\mathbf{F}(\mathbf{k}) \qquad (3)$$

where **F**(**k**) = F[**f**(**q**)]. This equation can be applied to a multispectral image to derive the edge content through the bands. Equation (3) is dubbed the Vector Laplacian. The band average of the output image given by equation (3) enhances the border and texture information of the original image.

2.4 Principal Component Analysis

Let f (**r**) be a multispectral image composed of η-bands, it is proposed to find a transformation of vector type formed as

$$g(s) = \mathbf{A}[f(r)] \quad (4)$$

In such a way, the operation of **A** on the pixels of the multispectral image f(r) produces a multispectral image, g(**s**) whose bands are decorrelated (Lira, 2010).

The eigenvectors of matrix **A** are dubbed principal components. The bands of g(**s**) associated with each eigenvector are also dubbed principal components. The bands of g(**s**) accumulate, in a decreasing way, the information contained in the original image f(**r**). Only the first principal component was retained.

3 Field work

The fieldwork was conducted in three regional areas. Two areas are located in the State of Zacatecas, known as Palmillas and Veta Grande. The third area is located in the State of Aguascalientes, known as Paso de Mexicanos (Figures 1a, 1b, 1c). As there are no accurate records of the regions where the old Royal Road vestiges can be found, citations of the approximate location of such places, by means of informants and known historical records, must be used (Gómez Arriola (eds.), 2012).

Once potential sites were located, fieldwork was conducted by surface routes, to search the areas of interest and to collect the necessary information. The geographic coordinates of the ground control points of the visited sites were acquired by means of a Global Position System (GPS) (Table 2). The general state of preservation of the visited sites was noted and photos were taken (Figures 4, 6, 8). The segments of the Royal Road were walked through several tens of meters to inspect and assess the state of the road. The next three sections provide details of the visited sites.

3.1 Veta Grande, Zacatecas

Veta Grande is one of the miner's municipalities where the Albarrada mine is located. From this mine, the extraction of gold, zinc and mainly silver was carried out. It is thought that thanks to this Veta Grande mine, discovered in the year of 1548, that the city of Zacatecas was founded. The Veta Grande town is just 8 km north from the city of Zacatecas. The section of the Royal Road ranging from the Veta Grande mine is practically destroyed, most of the road stone cladding is eroded and only some cobbles, with a maximum width of 5 meters, can be observed (Table 2, Figures 3, 4). The coordinates of the path were taken with a GPS. The road borders a brook that flows into the main town of Veta Grande where the mine is located. By the type of paving and its width, it is thought that it was only used as a branch to connect with the other main road.

3.2 Palmillas, Zacatecas

To reach this village it is necessary to move to the municipality of Ojo Caliente in Zacatecas and from there to the community of Palmillas, and finally travel a route of 3.5 kilometers to the Northwest of this town. This section is the best preserved of the three visited and consists of a continuous strip of rocks aligned and composed, in some sections, by cobblestone-like solid and large stones. The road runs in a straight line towards the town of Palmillas. The coordinates of the path were taken with a GPS and the inspection continued until the point where the pavement disappears (Table 2, Figures 5, 6). The extension that was traversed through corresponds to a section with a length of approximately 700 meters. Some sections were completely paved with a maximum width of 10 meters, other parts with only 5 meters.

3.3 Paso de Mexicanos, Aguascalientes

The Paso de Mexicanos village is located towards the community of Villa Garcia, Aguascalientes. This Royal Road section is located in the direction of the forts of Boca, Ojuelos and Cienega, whose location was strategically settled on the route of the silver. To get to this place, it is necessary to move towards the population known as Villa Garcia and then continue in a southeasterly direction for about 3.2 km. The terrain consists of hills that are occasionally bordered by some runoff, which are filled with water during the rainy season.

The inspection of such a section of the Royal Road indicated a construction of aligned rocks used to prevent erosion of the road, corresponding to the shoulder or sidewalls made of large stones. This is the only feature of the Royal Road that survives up to the present day. In the part where the pavement should be, only a kind of coating is observed on the bottom layer. This seems to be a tamping that acted as a binder where the stone was placed in the upper layer. The road was leveled, since the track is quite even, and follows the natural slope with gentle inclinations. The covered walkway extension was 600 meters, the width of which is about 5 meters (Figures 7, 8). The coordinates of the path were taken with a GPS (Table 2). At the site where a portion of the Royal Road experienced a ground a drop, along with a modern dirt road, the line of the old road disappears. It should be noted that in this region, the ground completely lacks any type of vegetation, which promotes erosion and as a result, has had a strong impact on the destruction of the road.

RESULTS

A pattern recognition problem is the basic nature of this research. The observation and identification of the remnants of the Royal Road is the first step to resolve such a problem. The second step is the quantification of the morphologic characteristics of the remnants, such as geographic location, length, orientation, actual path, and state of degradation. The procedure for the recognition of the remnants of the Royal Road can be conducted for the available satellite images and the known tracks from fieldwork. Nonetheless, high-resolution satellite images are required since the Royal Road segments are relatively narrow, with some degree of degradation, and partially covered by vegetation.

There are numerous roads in the three study areas. Some of such roads have similar spectral and spatial characteristics as the segments of the Royal Road. A visual inspection of the high-resolution images does not lead to unambiguous identification of the Royal Road. Therefore, a digital procedure is required combined with fieldwork. The Vector Laplacian has been used successfully to enhance the texture and the first principal component possess a property to enhance the edges and the reflectivity of the roads.

The Vector Laplacian operator was applied to the four bands of the images. The bands of the resulting vector field were averaged (Section 3.2.2). The resulting image provides an enhancement of the texture of the Royal Road segments.

Principal component analysis was applied to the bands of the images (section 3.2.3). Only the first component was retained. This first component shows an enhancement of the contrast between the Royal Road segments and its environs.

An RGB false colour composite was prepared using the image produced by the Vector Laplacian, the first principal component, and band 4. The RGB was formed as RGB = [Laplacian, PC1, B4). The RGB composites are shown in figures 3, 5 and 7. A red arrow points to the location where the geographic coordinates and assessment of the Royal Road segments were acquired in the fieldwork task. A detailed description of the three study sites is provided in the next sections.

1 Veta Grande, Zacatecas

This segment is closed to the small town Veta Grande in the State of Zacatecas; its access is relatively easy. The length of this segment is close to 1,000 meters. This segment belongs to a secondary road to connect an ancient mine. Even though with a major degradation, this segment shows the best visibility due to the contrast and difference in texture with respect to the entourage.

2 Palmillas, Zacatecas

This segment is away from a town or a highway, its access is difficult only by bare foot. The segment shows medium degradation, but it is barely visible due to small brushes growing in the middle and along the stones that form the road. The length of this segment is close to 1,200 meters. The westward part of this segment shows poor visibility, while the eastward is clearly distinguishable in the image.

3 Paso de Mexicanos, Aguascalientes

This segment is not near any town or a highway, therefore its access is only by bare foot. The segment is barely visible due to a major degradation and the vegetation intermingled with the stones that form the road. The length of this segment is close to 2,000 meters. The westward part of this segment is barely visible in the image, while the eastward is easy to appreciate in the image. This segment is formed by to straight roads that change direction in the crossing a mayor geologic feature in the terrain.

Conclusions

The Royal Road of the Interior Land is a valuable archaeological heritage for humankind and in particular, for Mexico and the United States. The recognition of the actual segments of the Royal Road is an important step for its preservation. The use of high-resolution satellite images, and pattern recognition techniques, set the basis for a precise identification of the actual state of the Royal Road. The mapping of the remains of the Royal Road, from Mexico City to Santa Fe, NM, is a major task that requires extensive fieldwork and substantial funding. The enhancement techniques, to produce evidence of the segments of the Royal Road, are well known procedures and need no further analysis.

A possible recommendation for future work on identification and assessment of the Royal Road would be to use multispectral images of a 30 cm pixel with four bands. However, such images are more expensive that the images used in this research with a pixel of 50 cm and four bands. An important aspect to be considered is the availability of cloud-free images of the zones where segments of the Royal Road are known to exist.

The Royal Road of the Interior Land ranged 3,000 kilometers from Mexico City and Santa Fe, NM, USA. Many branches were connected to the main track. The Royal Road was an important element of economic, social and political development during the colonial times of Mexico. The recognition of the surviving segments is required to preserve the cultural heritage of Mexico. The present research is a first step in such a major effort.

ACKNOWLEDGMENT

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TABLES

Table 1.- Basic technical details of Pleiades Images of study sites

Sensor	Date	Spectral Bands (nm)	Dimension (Pixels)	Pixel (m^2)
Pleiades 1B	November 17, 2017	Pan: 480 - 830	10,849 × 10,549	0.5 × 0.5
		Blue: 430 - 550		1.5 × 1.5
		Green: 490 - 610		1.5 × 1.5
		Red: 600 - 720		1.5 × 1.5
		NIR: 750 - 950		1.5 × 1.5
Pleiades 1A	September 13, 2017	Pan: 480 - 830	9,154 × 9,607	0.5 × 0.5
		Blue: 430 - 550		1.5 × 1.5
		Green: 490 - 610		1.5 × 1.5
		Red: 600 - 720		1.5 × 1.5
		NIR: 750 - 950		1.5 × 1.5
Pleiades 1A	November 23, 2017	Pan: 480 - 830	1,768 × 1,672	0.5 × 0.5
		Blue: 430 - 550		1.5 × 1.5
		Green: 490 - 610		1.5 × 1.5
		Red: 600 - 720		1.5 × 1.5
		NIR: 750 - 950		1.5 × 1.5

Level 1A - Correction of radiometric anomalies. Cartographic projection UTM, WGS84.

Table 2. Location of sites of known segments of the Royal Road.

Location	Coordinates	Description	Figures
Veta Grande	22° 51' 58.158", -102° 32' 42.375"	Major degradation	4
Palmillas	22° 39' 43.022", - 102° 22' 48.874"	Medium degradation	6
Paso de Mexicanos	22° 11' 3.308", - 101° 58' 30.838"	Major degradation	8

FIGURES

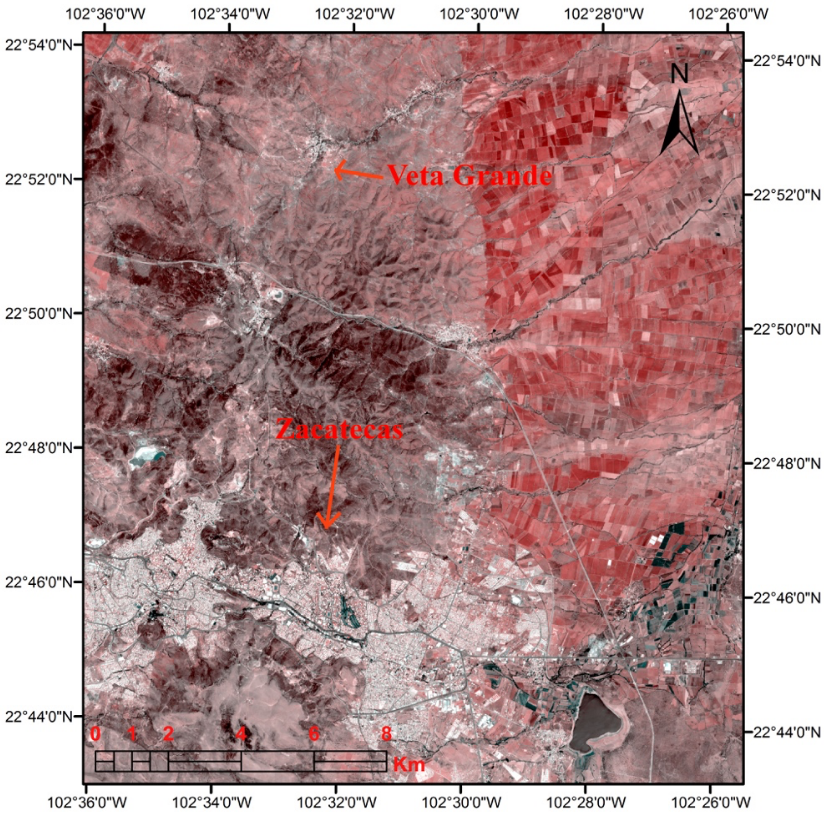

Figure 1a. Location map of Veta Grande segment.

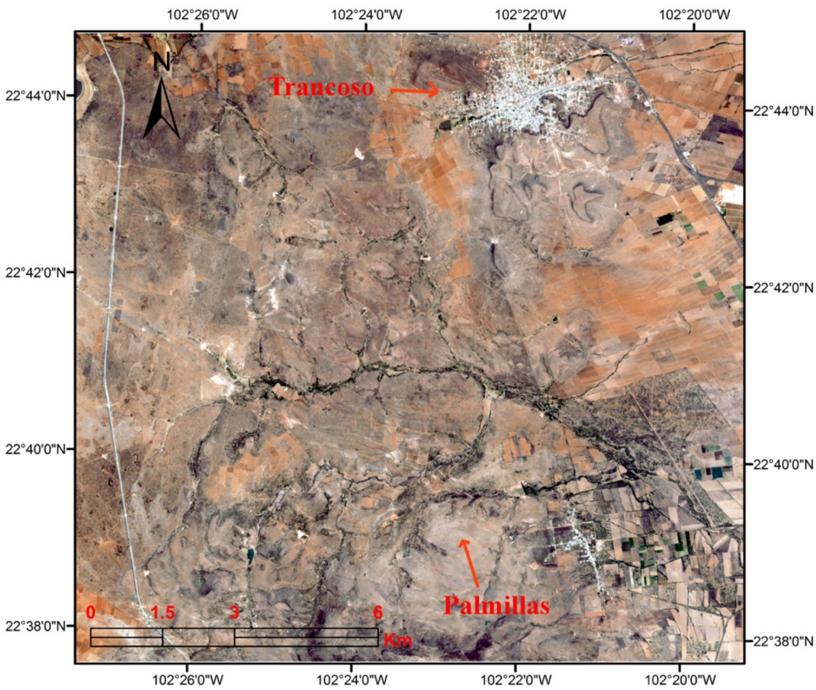

Figure 1b. Location map of Palmillas segment.

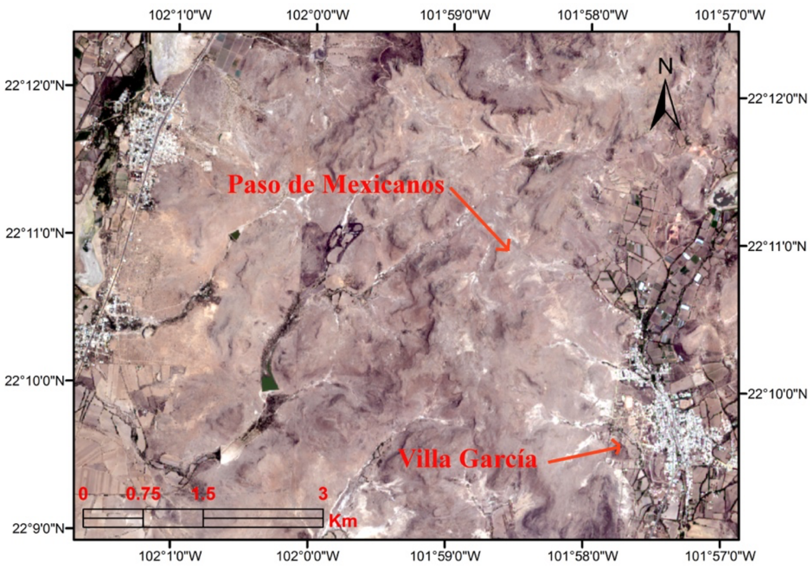

Figure 1c. Location map of Paso de Mexicanos segment.

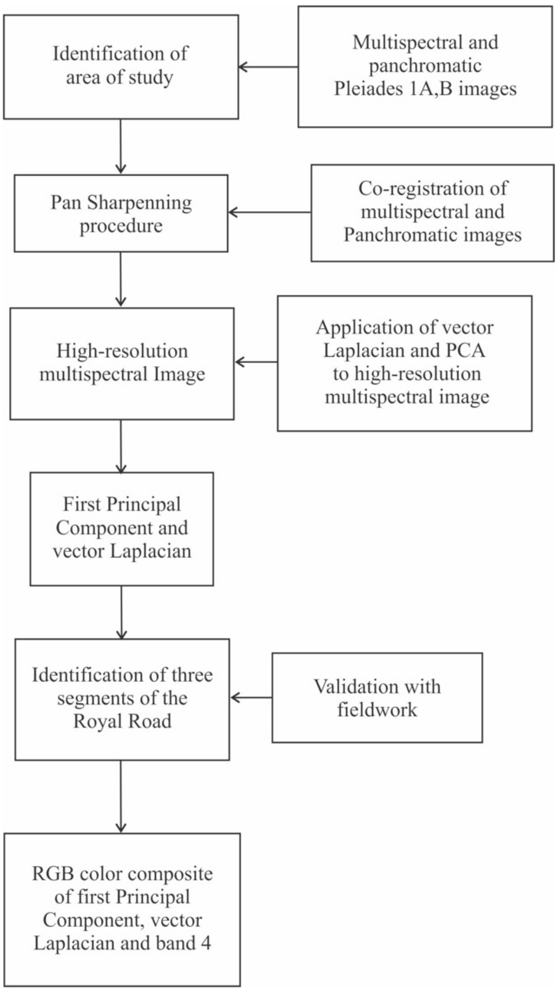

Figure 2. Block diagram of the enhancement and sharpening process.

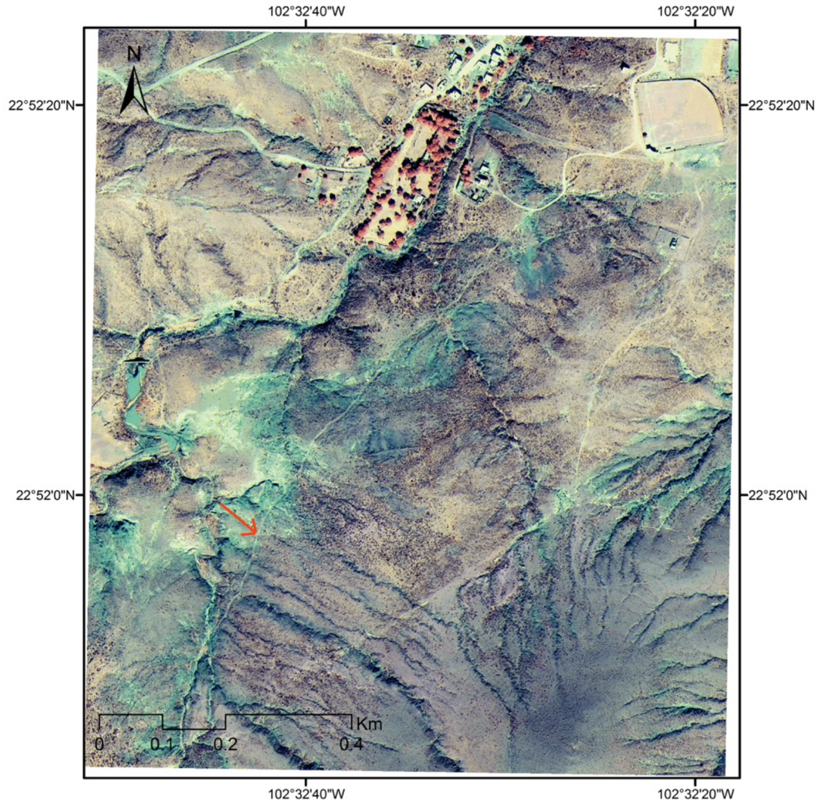

Figure 3. The segment of the Royal Road dubbed Veta Grande, runs from Southwest to Northeast. The RGB = [Laplacian, PC1, B4). The red arrow points to the location of field work and the geographic coordinates shown in table 1

Figure 4. Mosaic of the identification of the segment of the Royal Road in Veta Grande, Zacatecas. Photos of the aspect of the road.

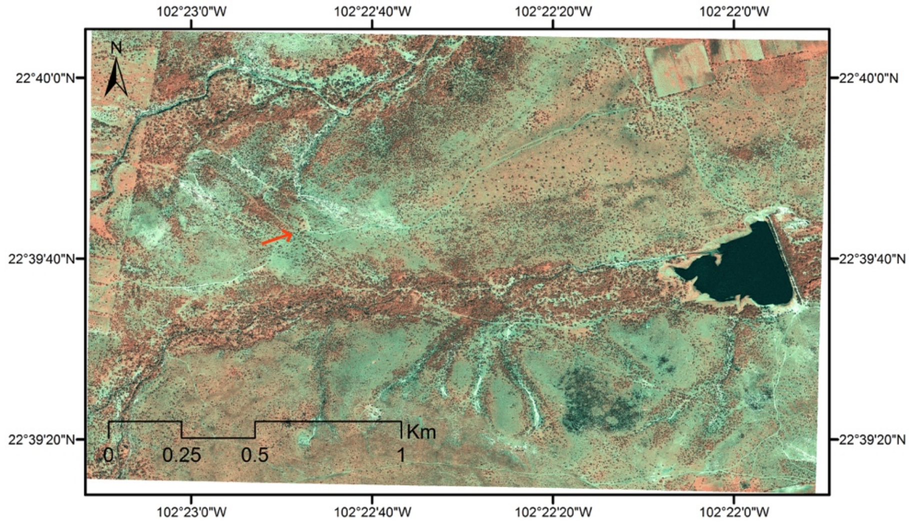

Figure 5. The segment of the Royal Road dubbed Palmillas, runs from Southeast to Northwest. The RGB = [Laplacian, PC1, B4). The red arrow points to the location of field work and the geographic coordinates shown in table 1.

Figure 6. Mosaic of the identification of a segment of the Royal Road in Palmillas, Zacatecas. Photos of the aspect of the road.

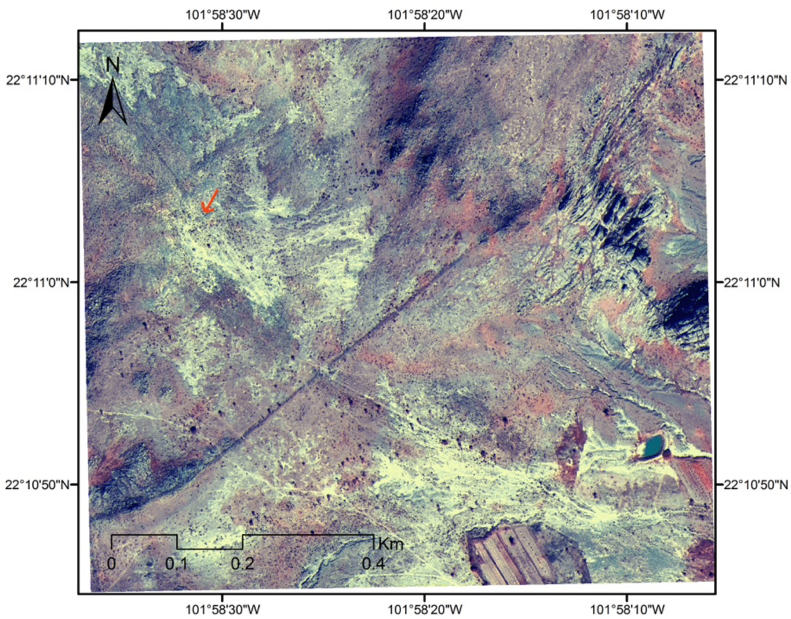

Figure 7. The segment of the Royal Road dubbed Paso de Mexicanos, runs from North West to North East. The RGB = [Laplacian, PC1, B4). The red arrow points to the location of field work and the geographic coordinates shown in table 1.

Figure 8. Mosaic of the identification of a segment of the Royal Road in Paso de Mexicanos, Aguascalientes. Photos of the aspect of the road.