Application of remote sensing techniques in the estimation of surface temperature models as support for geothermal exploration in Colombia

Matiz-León Jhon Camilo¹, Alfaro-Valero Claudia María², Rodríguez-Rodríguez Gilbert Fabian³

¹ Geodetic Engineer. Magister in Information Sciences and Geomatics. Researcher in geological-geophysical modelling 3D, Geomatics and GIS. Geothermal research and exploration group. Colombian Geological Survey (SGC)
² Chemist. Geothermal Specialist. Geothermal research and exploration group chief. Colombian Geological Survey (SGC)
³ Geodetic Engineer. Researcher in magnetotelluric surveys. Geothermal research and exploration group. Colombian Geological Survey (SGC)

E-mail: jmatiz@sgc.gov.co¹, calfaro@sgc.gov.co², gfrodriguez@sgc.gov.co³

Abstract. The obtaining of models of surface temperature by means of Shallow Surface Temperature - SST, shows a first approach to surface temperature anomalies in the exploration stage of a geothermal area of interest in a fast, portable and economic way. In the Colombian Geological Service - SGC, the SST materializes at depths between 20 cm and 150 cm deep, taking into account the normalization of data to eliminate the influence of solar radiation, thermal diffusivity, albedo, slopes, relief, the effect of climatic seasons. As a method parallel to the estimation of models of temperature of the terrestrial surface, the Remote Sensing - RS are integrated that have satellite images of terrestrial observation in the thermal infrared. Based on the ground truth established by the SST, the degree of positive or negative correlation is calculated with the temperature models estimated by RS, reaching a method of validation between remote sensing techniques and ground truth. Within the proposed methodology, the processing of a temperature model from RS images is proposed, specifically the processing of images with bands in the thermal infrared (such as Landsat 8 TIRS) of the geothermal area. The validation of the model achieved through the DIP - Digital Image Processing, is performed against the ground truth (SST) through qualitative and quantitative analysis with variables such as vegetation indexes or anomalies of elements such as Uranium - U, Thorium - Th and Potassium - K by gamma ray spectrometry, according to the availability of information in each geothermal area. In order to establish a positive or negative correlation between the temperature anomalies estimated from different techniques (SST vs RS), parametric correlation tests were performed pixel by pixel (Pearson coefficient).

1. Introduction
The One of the sources of thermal data associated with the earth's surface is derived from Earth Observation satellites placed in orbit. These sensors allow to capture values of radiance in the near infrared, included in the digital levels of the pixel that by means of the digital processing of the image can express values in units of temperature [14]. Since taking the image suggests that the wavelength is...
affected by the interference of solar radiance, vegetation and climate, a series of corrections are applied to the digital level to calculate the temperature values and vegetation indices that adjust to the geothermal reality [1]. To validate these models derived from the RS, as ground true, we have the Shallow Surface Temperature - SST for the characterization of temperature anomalies near the earth's surface [14].

The cost-benefit evaluation in the exploration stage takes a lot of relevance in the interpretation of the temperature anomalies present in the geothermal systems [16]. Due to this, the contribution in the characterization of temperature anomalies from models extracted by remote sensing, lies in the contribution of this input in the pre-feasibility stage of the study area for decision-making aimed at identifying the elements and components of the geothermal area [15]. This contribution is essential, since generally the stage of exploration in the nonexistent geothermal industry in the Colombian territory consumes many financial resources dedicated to the identification of the elements of the conceptual model to evaluate the energy potential [2, 10, 12, 16].

2. Methodology
The research methodology corresponds to the processing of a temperature model from SR images, specifically the processing of Landsat 8 TIRS images (bands 10 and 11) of the geothermal area. In turn, it includes the calculation of vegetation indexes, generated with the bands of visible red and near infrared - NIR [4] of Landsat 8 OLI images (bands 4 and 5), which allows spatially identify the density and type of living vegetation, in order to corroborate the spatial variations of the surface temperature with the presence of vegetation [15]. The validation of the model achieved through the DIP - Digital Image Processing, was performed against the ground truth constructed through the SST by means of the qualitative analysis of the treatments generated for each image. In order to establish a quantitative measure of the relationship between the variables (calculated temperature by the SST and SR), parametric correlation tests (Pearson) were performed due to the normality of the data [3].

2.1. Materials

2.1.1. Landsat 8 TIRS and OLI. The processed images are downloaded under criteria such as shooting dates close to the dates of SST drilling and cloudiness less than or equal to 10% in each scene [10]. From these images, the thermal bands numbers 10 and 11 of the Thermal InfraRed Sensor - TIRS, with wavelengths of 10.60 µm - 11.19 µm and 11.50 µm - 12.51 µm, respectively, with spatial resolution of 100 m, rerouted at 30 m and the red bands, were used. The band with the near infrared of the Operational Land Imager - OLI sensor (wavelength between 0.64 µm to 0.88 µm with spatial resolution of 30 m) [20].

2.1.2. Digital Elevation Model – DEM. The heights of the study area are based on the Digital Elevation Model - MDE of the National Aeronautics and Space Administration - NASA and the National Geospatial Intelligence Agency - NGA, known as the Shuttle Radar Topography Mission - SRTM with a precision global of 1 second of arc or in reference systems projected at 30 m [8]. The SRTM uses the C band of the Aerospace Radar Imaging platform and the X band of the Synthetic Aperture Radar (X-SAR).

2.2. Methods

2.2.1. Surface Temperature. The surface temperatures are calculated from the data taken in the field by drilling the wells to the depths of 20 cm, 100 cm and 150 cm, with a separation distance between soundings of 1 km of spacing [6, 18]. For the representation of the temperatures, a statistical analysis was generated for each of data sets at different recorded depths, composed of Quantil - Quantil (Q – Q) diagrams, semivariograms and the review of the global trend of the data [18]. The calculation of the
surface temperature was based on (1), where $T_\text{s}$ corresponds to the annual average air temperature in °C and $h$ to the altitude in m [7].

$$T_\text{s} = 28.1 - 0.00553 \times h$$  

(1)

2.2.2. Normalization of temperatures with reference to $T_\text{s}$. Once the $T_\text{s}$ has been calculated, the temperature data for the measured depth are normalized, taking into account that the shallow temperature were measured at different times and that the daily variation of the solar rays affects each one of the recorded values [19]. This normalization, with the purpose of eliminating the effect of the sun in each one of the surveys, is based on the difference of the temperatures found in depth and the $T_\text{s}$ (2). Where $T_\text{norm}$ is the normalized temperature and $T_\text{prof}$, the temperature measured in depth. This standardization is applied for each of the depths reached [19].

$$T_\text{norm} = T_\text{prof} - T_\text{s}$$  

(2)

2.2.3. Geostatistics. The Simple Kriging method was applied, using the theoretical model of the Gaussian variogram, a lag or lag (h) of up to 1000 m distance and a neighborhood parameter corresponding to the number of neighbors involved in the spatial interpolation (15 surveys) [18]. In Figure 1, interpolations are represented for temperatures reached at 150 cm depth.

![Figure 1. Interpolated temperatures with geostatistics at depths of 150 cm](image)

2.2.4. Surface Temperature from Digital Number - DN. The calculation of the temperatures from the Landsat 8 images, consists of the transformation of the Digital Numbers - DN to radiance values by means of (3) [20]. In the metadata of each image are the respective radiometric rescaling coefficients: $\text{radiance}_{\text{multiband}_x}$ corresponds to the multiplicative adjustment factor of the radiance in each band. $\text{band}_{\text{thermal}_x}$ corresponds to thermal band of the TIRS sensor to be used. $\text{radiance}_{\text{add}_x}$ corresponds to the additive factor of radiance adjustment in each band used [20]. This procedure can be applied in (3) and (4) for bands 10 and 11 of the TIRS sensor [11].

$$\text{radiance}_{\text{multiband}_x} \times \text{band}_{\text{thermal}_x} + \text{radiance}_{\text{add}_x}$$  

(3)
Subsequently the radiance is transformed into apparent brightness temperature values $T_{Kelvin}$ (4), where $K1$ and $K2$ correspond to the thermal conversion constants for each band of the image and $L\lambda$ is the reflectance in the upper part of the atmosphere - TOP (Top of Atmosphere) [20]. The calculated temperature is represented in degrees Kelvin, so it is transformed to degrees Celsius (equation 5) [20]. This procedure can be applied for bands 10 and 11 of the TIRS sensor [11]. In Figure 2, the temperatures calculated from the Landsat 8 TIRS sensor images are shown.

$$T_{Kelvin} = \frac{K2}{ln\left(\frac{K2}{K3+1}\right)} \quad (4)$$

$$T_{Celsius} = T_{Kelvin} - 273.15 \quad (5)$$

![Figure 2](image)

**Figure 2.** Temperatures calculated with the thermal bands of Landsat 8 TIRS

2.2.5. *Normalization of temperatures with reference to the Sensor Surface Temperature.* To compare the temperature differences in depth by eliminating the effect of the sun, normalization was applied to temperature values calculated from the Landsat thermal bands, based on the surface temperature calculated with TIRS - $T_{Sup.Landsat}$.

2.2.6. *Vegetation Indexes.* In the estimation of the Normalized Differential Vegetation Index - NDVI, the reflectance DN of the visible red and NIR were transformed into indices for each pixel, by (6) [13]. The values to measure the vegetation in the NDVI range from -1 to +1, where the values higher or close to 1 represent a vegetative cover with greater greenness (mostly healthy and free of stress) [13]. In Figure 3, the result achieved for a geothermal area in exploration is observed.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (6)$$
Figure 3. Normal Differentiated Vegetation Index - NDVI with the red and near infrared bands of Landsat 8 OLI

3. Validation

3.1. Correlation between pixel to pixel variables: Pearson coefficient

A correlation coefficient measures the degree of relationship between two random variables [17]. The Pearson coefficient (7) measures the degree of association between two quantitative random variables with normal bivariate normal distribution [3]. Where $\rho_{XY}$ is the correlation coefficient of Pearson, $\sigma_{XY}$ the covariance of the variables $XY$, $\sigma_X$ the standard deviation of the variable $X$ and $\sigma_Y$ the standard deviation of the variable $Y$ [17].

$$\rho_{XY} = \frac{\sigma_{XY}}{\sigma_X \sigma_Y}, \text{ donde } -1 \leq \rho_{XY} \leq 1 \quad (7)$$

For the correlation analysis between the same temperature variable from two different sources of information (ground truth = SST and hypothesis = RS), the correlation was made pixel by pixel, by transforming each image (interpolated and processed) as a matrix array and treated under the processing of statistical software (Table 1).

| Variables | Pearson Coefficient |
|-----------|---------------------|
| Temperature calculated based on heights vs temperature calculated by RS for 15/Sep/2015 | 0.2104 |
| Temperature calculated based on heights vs temperature calculated by RS for 20/Nov/2016 | 0.1928 |
| Temperature calculated based on heights vs temperature calculated by RS for 23/Ene/2017 | 0.4388 |

| Variables | Pearson Coefficient |
|-----------|---------------------|
| Temperature measured in surface vs temperature calculated by RS for 15/Sep/2015 | 0.2746 |
| Temperature measured in surface vs temperature calculated by RS for 20/Nov/2016 | 0.0547 |
| Temperature measured in surface vs temperature calculated by RS for 23/Ene/2017 | 0.3627 |
3.2. Analysis of Cross Sections

To compare the positive and negative anomalies and the respective correlation between variables, crossed sections are drawn, covering the areas of interest in the work area, which allow to identify the variations along the profile of the topography (height above the level of the sea), the temperature according to the depth of measurement, the day of capture of the sensor and the vegetation indexes and variables that enrich the interpretation and for which data are available, such as Uranium - U, Thorium - Th and Potassium - K (Figure 4) [9].

![Figure 4. Anomalies of a) Uranium, b) Thorium and c) Potassium for the geothermal area of Paipa](image)

Figure 5 shows an example of cross section with the intersection on the same section of variables such as surface temperature, temperature in depth, anomalies of different elements and topography.
4. Discussion and Conclusions
The consolidation of the RS as a tool for the generation of surface temperature models, is strengthened as a real option for the exploration of geothermal resources in the areas of interest in the colombian territory. The implementation of these results together with the SST, allow to build a preliminary view of the heat distribution in the geothermal areas under exploration, integrating the values reached at different depths and the influence of geological and geochemical factors together with the topography, granting a first indication of the geothermal structure of the area, allowing to improve the decision making in future studies.

The SST as ground truth, constitute a first perspective of the heat distribution in the geothermal exploration areas. In turn, the remote sensing provide validation of the geothermal structure of the area, through the integration of the NDVI, anomalies of elements such as uranium, thorium and potassium and the estimated temperatures for the various days of study. The influence of topography is an important criterion due to the influence of this variable both for the achievement of field
measurements and for the interference of the altitude in the correction factors at the digital levels of the satellite image.

The estimation of the coefficients of the Pearson correlations greatly constrains the validation of the results found by means of RS versus ground truth (SST). This form of validation provides the user with a reliable methodology that allows to compare the results achieved through the digital processing of satellite images. These techniques take place with a point of control derived from what is observed in the field, adding to the initial inputs that permit the identification of a geothermal area with all its components.

The characterization of the temperature anomalies found in the areas of interest present in Colombia have the potential to reduce costs and constrict the components of a geothermal area in the early exploration stage. In turn, for direct uses, specifically in the installation of heat exchangers for domestic use, they are very useful, since when mapping the anomalies near the surface, a direct relationship is established with the depths where the water can be exploited resource in this way.

The processing of images with data in the thermal infrared bands, allows to give a first guideline in the identification of possible temperature anomalies near the surface that do not necessarily depend on a convective heat flow system, thus being able to interpret with a first tool temperature variations for conductive geothermal systems (such as those present in sedimentary basins).

References
[1] Abouriche M 1989 Temperature measurements at the surface and in shallow drillholes ONU Geothermal Training Programme Reykjavik Islandia Reporte 8
[2] Beardsmore G 2012 Towards a shallow Heat Flow probe for mapping thermal anomalies Proceedings: Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University Stanford California EEUU 37 pp. 1-142
[3] Baddi M Guillen O Lugo Serrato O and Aguilar J 2014 Correlación No-Paramétrica y su Aplicación en la Investigaciones Científicas International Journal of Good Conscience 2(9) pp. 31-40
[4] Becerra-González L Matiz-León C Ariza-Ariza O Borda-Beltrán D and Medina J 2016 Aplicación de imágenes de satélite y de sistemas UAV para la producción de guayaba en la provincia de Vélez, Santander UD y la Geomática 11 46-53
[5] Coolbaugh M Sladek C Zehner R and Kratt C 2014 Shallow Temperature Surveys for Geothermal Exploration in the Great Basin, USA, and Estimation of Shallow Aquifer Heat Loss GRC Transactions 38 pp 115-122
[6] Coolbaugh M Sladek C Faulds J Zehner R and Opplieger G 2007 Use of rapid temperature measurements at a 2-meter depth to augment deeper temperature gradient drilling Proceedings: Thirty-Second Workshop on Geothermal Reservoir Engineering Stanford University Stanford California
[7] Eslava J 1992 Perfil altitudinal de la temperatura media del aire en Colombia Geofísica Colombiana 1 pp 37-52
[8] Farr T Rosen P Caro E Crippen R Duren R Hensley S Kobrick M Paller R Rodriguez E Roth L Seal D Shaffer S Shimada J Umland J Werner M Oskin M Burbank D and Alsdorf D 2007 The Shuttle Radar Topography Mission Reviews of Geophysics 45(2) pp 1-33
[9] González L Vásquez L Muñoz R Gomes H Parra do G and Vargas S 2008 Exploración de recursos energéticos Exploración de Uranio en Paipa, Iza, Pesca, Chivata (Boyacá) Ingeominas Bogotá D.C.
[10] Kratt C Coolbaugh M Peppin B and Sladek C 2009 Identification of a New Blind Geothermal System with Hyperspectral Remote Sensing and Shallow Temperature Measurements at Columbus Salt Marsh, Esmeralda County, Nevada Geothermal Resources Council Transactions 33 pp 481-485
[11] Li M Liu S Zhou H Li X and Wang P 2005 The Temperature Research of Urban Residential Area with Remote Sensing Proceedings IEEE International Geoscience and Remote Sensing
[12] Matiz-León J C 2015 Modelo conceptual geológico – geofísico del área geotérmica de Paipa, Boyacá Technical Report Grupo de Exploración de Recursos Geotérmicos Servicio Geológico Colombiano – SGC Bogotá D.C.

[13] Mermer A Yildiz H Ünal E Aydoğdu M Özaydın A Dedeoğlu F Urla O Aydoğanş O Torunlar H Tuğac M Avağ A Ünal S Mutlu Z 2015 Monitoring rangeland vegetation through time series satellite images (NDVI) in Central Anatolia Region Fourth International Conference on Agro-Geoinformatics (Agro-geoinformatics) Estambul pp 213-216

[14] Mwawongo G 2007 Geothermal mapping temperature measurements”. Short Course II on Surface Exploration for Geothermal Resources, organized by UNU-GTP and KenGen Lake Naivasha Kenya

[15] Norini G Gropelli G Sulpizio R Carrasco-Núñez G Dávila-Harris P Pellicioli C Zucca F and De Franco R 2015 Structural analysis and thermal remote sensing of the Los Humeros Volcanic Complex: Implications for volcano structure and geothermal exploration Journal of Volcanology and Geothermal Research 301 pp 221-237

[16] Olmsted F and Ingebritsen S 1986 Shallow subsurface temperature surveys in the basin and range province - II. Ground temperatures in the Upsal hogback geothermal area, west - Central Nevada U.S.A. Geothermics 15(3) pp 267-275

[17] Restrepo L and González J 2007 De Pearson a Spearman Revista Colombiana de Ciencias Pecuarias 20 pp 183-192

[18] Rodríguez G 2016 Análisis de la distribución de calor en el área geotérmica del Volcán Azufral a partir de sondeos superficiales de temperatura Technical Report Grupo de Exploración de Recursos Geotérmicos Servicio Geológico Colombiano – SGC Bogotá D.C.

[19] Rodríguez G 2013 Sondeos Térmicos Superficiales en el área geotérmica de Paipa, Boyacá Technical Report Grupo de Exploración de Recursos Geotérmicos Servicio Geológico Colombiano – SGC Bogotá D.C.

[20] USGS 2016 Landsat (L8), Data Users Handbook Sioux Falls South Dakota U.S. Geological Survey