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Method for vertical accuracy

assessment of digital elevation models derived from remote sensing data

Metodología para evaluación de la exactitud posicional vertical de los modelos digitales de elevación derivados de sensores remotos

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Abstract

The objective of the present study was to propose a method for evaluating the vertical accuracy of digital elevation models (DEMs), which is applicable to the quality control process in the production line of the Sub-Directorate of Geography and Cartography of the Agustín Codazi Geographic Institute (Subdirección de Geografía y Cartografía del Instituto Geográfico Agustín Codazzi [IGAC]), which also fulfills the institutional quality objectives. The proposed method outlines the steps for the following: 1) the definition of acceptance levels based on an uncertainty analysis of the sources of error inherent to DEMs; 2) the determination of the sampling design (method and size) as a function of the terrain characteristics (slope and cover); and 3) the assessment of the vertical accuracy based on different statistical measures for quantifying the error. The effectiveness of the method was tested through its application to a DEM data set generated by the Sub- Directorate of Geography and Cartography of IGAC.
KEY WORDS: vertical accuracy assessment; digital terrain model; digital elevation model.

Resumen

El objetivo del trabajo fue obtener una metodología para evaluar la exactitud posicional vertical de los modelos digitales de elevación, aplicable en el proceso de control de calidad, en la línea productiva de la Subdirección de Geografía y Cartografía del Instituto Geográfico 'Agustín Codazzi' (IGAC), dando cumplimiento así a los objetivos de calidad institucionales. La metodología propuesta comprende: 1) la definición de niveles de aceptación, a partir del análisis de incertidumbre de las fuentes de error inherentes al DEM; 2) la determinación del diseño muestral (método y tamaño), en función de las características del terreno (pendiente y cobertura), y 3) la evaluación de la exactitud vertical, a partir de diferentes medidas estadísticas para cuantificar el error. La efectividad de la metodología fue evaluada mediante su aplicación a un conjunto de datos de DEM generados por la Subdirección de Geografía y Cartografía del IGAC.
PALABRAS CLAVE: evaluación de exactitud vertical; modelo digital del terreno; modelo digital de elevación.

1. Introduction

Digital elevation models (DEMs) continuously and quantitatively represent the elevation of the Earth's surface and contain positional data on the horizontal (x), vertical (y), and elevational (z) axes of a Cartesian plane, which can be used to generate contour lines and topographic profiles, among other map products (Rui *et al.*, 2016).

The objective of the present study was to design a method for assessing the vertical accuracy of DEMs generated by the Agustín Codazzi Geographic Institute (Instituto Geográfico Agustín Codazzi [IGAC]) in fulfillment of the objectives of producing, providing, and disseminating information and knowledge in matters of cartography, agrology, land registries, geography, and geospatial technologies and to standardize the management of such data in support of comprehensive planning and development processes in Colombia. The study was led by the Internal Working Group (Grupo Interno de Trabajo [GIT]) of the Remote Sensing and Geographic Applications Branches under the coordination of engineers Mauricio Ramírez Daza of the Center for Research and Development of Geographic Information (Centro de Investigación y Desarrollo en Información Geográfica [CIAF]) and Alexander Páez Lancheros of the Sub-Directorate of Geography and Cartography (Subdirrección de Geografía y Cartografía) of IGAC, Bogota, Colombia.

The results describe the proposal of a method for assessing the vertical accuracy of DEM data sets and outline the procedures for applying this method. In particular, the proposed method supports the establishment of applicable quality measures with respect to institutional quality objectives and the technical and the technical specifications of DEMs generated by the Instituto de Geografía 'Agustín Codazzi' (IGAC).

2. Materials and methods

2.1 Study area

The study area is located in the municipality of Santiago de Cali in the department of Valle del Cauca (Colombia) and has an area of 20089.10 ha, an elevation of 955 masl, and an average temperature of 23 °C. It contains mountainous, undulating, and flat terrain and encompasses the cliffs of Cali, whose diversity of ecosystems is reflected in the wide variety of climates, with temperatures that range from 25 °C in the piedmont to 5 °C in the paramos and elevations from 200 to 4.100 masl (FIGURE 1), (Ministerio de Ambiente & Desarrollo Sostenible, 2015).

Several land cover types are present in the area, including pastures, crops, and natural areas (vegetation or forest remnants). The main productive activities are agriculture (sugarcane crops), livestock ranching, commerce, industry (paper, plastic, textile, charcoal, agricultural and industrial machinery and medicine) and transport (Murgueitio & González-Cabo, 2015).

2.2 Definition of image types

During the testing stage, several inputs were used. First, a land cover layer of Colombia based on the Corine land cover method for the 2007–2010 period, which was interpreted from satellite images from the year 2007 (Path Row 9-58), was obtained. In addition, a reinterpretation of the cover of urban areas, cropland, and pastures was performed using orthophotos of the cliffs and of Cali. The aerial photos over the cliffs were taken using a Vexcel Ultracam-D sensor at a 1:5.000 scale on 11 August 2010 and had a coverage of 23604.52 ha. The flights for the orthophoto mosaic of Cali were performed during the months of March, April and July 2009, covering an area of 39.252 ha.

In addition, two DEMs derived from radar interferometry and photogrammetry were used. The first DEM was generated using a GeoSAR sensor.

FIGURE 1 Location of the study area.
SOURCE: ELABORATED BY THE AUTHORS USING DATA FROM IGAC

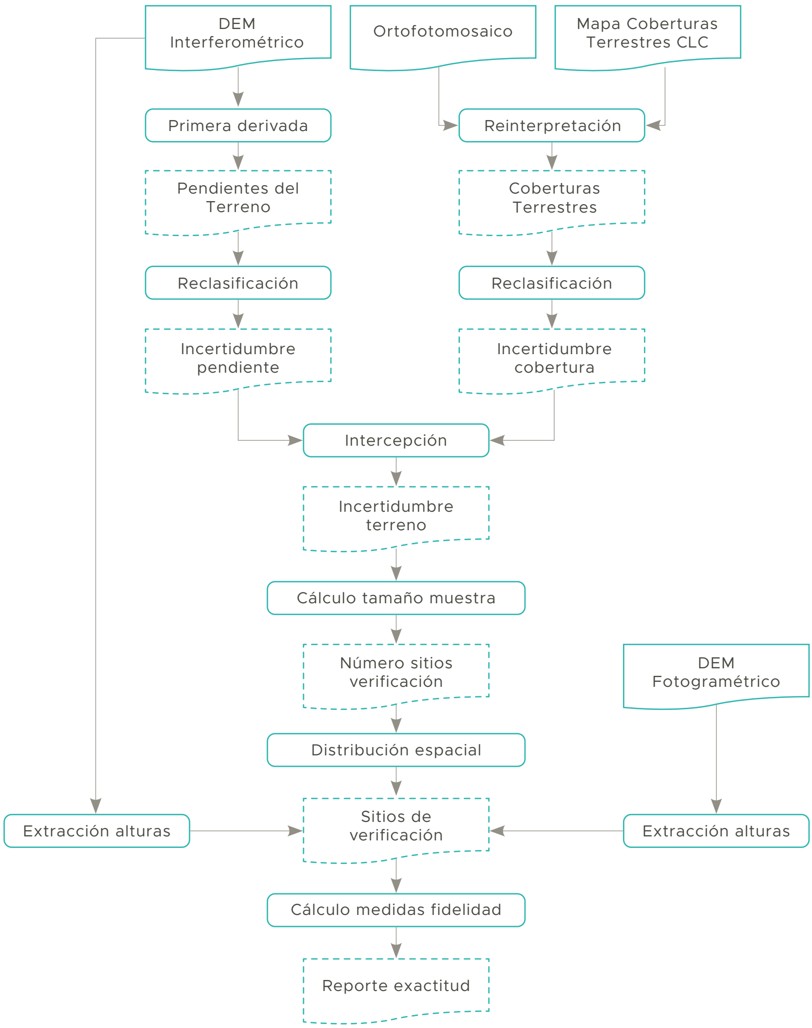
The data are expressed in the Cartesian coordinate system, origin San Antonio, and are based on the reference framework of the Former National Geodesic Network (Antigua Red Geodésica Nacional [Arena]), a Cartesian system of local origin used for cartography at scales of 1:5.000 or smaller.

3. Methods

The present assessment method of the vertical accuracy of the DEMs for the implementation of quality control processes within the production line of the Sub-Directorate of Geography and Cartography of IGAC is based on a subset of fundamental principles for evaluating the quality of the geographic information, which is generally known as best practices (FIGURE 2).

Best practice recommendations comprise three fundamental aspects: sampling design, response design, and analysis of the results. The main best practice recommendations for evaluating the positional accuracy of the DEMs are as follows: 1) define the level and method of inspection according to the characteristics and objectives of the DEM to be evaluated; 2) identify uncertainties associated with the terrain; 3) access sources of greater accuracy; 4) select the type of sampling; 5) determine the sample size; 6) implement a probabilistic sample design that allows the main objectives of the quality assessment to be achieved and that additionally responds to practical limitations related to, for example, the cost and availability of reference data; 7) implement a response design protocol based on spatially and temporally representative sources of reference data to validate each sampling unit (the values of the control points are considered to be *true* values, which means that they are measured without error, with respect to the values of the DEM to be evaluated); and 8) implement a coherent analysis with a sampling plan and response design protocols (Iwahashi *et al.*, 2018).

FIGURE 2 Diagram of the methodological design.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA



3.1 Definition of the level and method of inspection

First, it is necessary to establish the most appropriate level and method of inspection for evaluating the vertical accuracy of the DEMs. The International Organization for Standardization (ISO) defines, in norm 19114 of 2009 and with respect to 'Quality Assessment Procedures', that the quality control of geographic information guarantees the appropriate use of geographic data in certain applications (Instituto Geográfico Nacional, 2017). In the case of Colombia, the technical Colombian norm NTC 5660 (Instituto Colombiano de Normas Técnicas y Certificación (Icontec, 2010), in reference to 'Quality Assessment: Processes and Measures' (Evaluación de la calidad. Procesos y medidas) outlines the possibility of performing such an assessment using either a direct or indirect method.

In the direct method, the quality of a particular data set is evaluated through comparison with internal or external reference information. In the direct internal method, the reference data form part of the evaluated data set, whereas in the direct external method, reference data that are external but related to the data set are used in the comparison. To determine the appropriate inspection level for evaluating the accuracy of a DEM, the following points should be considered:

The extension of the geographic area and scale of the DEM should be accounted for because the demands of the analysis could differ on this basis.

The unit that best defines the characteristics and objectives of the DEM to be evaluated (geographic area, tile, series, lot, and so on) should be defined and considered in the quality control analysis.

A complete inspection is recommended only for a small DEM, given the high cost.

A partial inspection is appropriate for DEMs that were produced under high quality standards.

The data of the DEMs should be grouped for easy identification; additionally, it is necessary to determine whether a particular DEM is to be evaluated in an isolated manner or whether it forms part of a continuous data set.

If the project budget and conditions of the study area are suitable, then a direct external method should be employed, and a total inspection should be conducted.

In cases where the DEMs cannot be evaluated by means of a direct external method, a direct internal method should be used.

The indirect method is recommended only if the secondary sources to be used in the assessment of the DEM are of greater quality.

The results obtained after performing the inspection will lead to the rejection or acceptance of the evaluated DEM; rejected DEMs should be corrected and newly inspected to guarantee their quality.

3.2 Identification of uncertainties associated with the terrain

In DEM assessments, a data source of greater accuracy should be used to validate the model, although the level of uncertainty of many sources is often not stated (Ariza, 2013). In addition, many studies have shown that the accuracy of DEMs varies with the terrain and cover type (Bater & Coops, 2009).

The level of uncertainty in the DEMs can also be associated with the type of technology used for data acquisition. For example, with LIDAR technology, the presence of dense vegetation associated with forests can be defined (TABLE 1); however, in areas of dense vegetation, pulses emitted from LIDAR sensors can be blocked from reaching the ground. This consideration is a decisive factor that affects the uncertainty of the DEMs. Kraus & Pfeifer (2001) confirm that fewer than 25% of LIDAR points penetrate forested areas. Additionally, an increase in the rugosity and slope of the terrain decreases the elevational accuracy by 0.5 to 1 m for a flight at a height of 1000 m (Estornell, 2011). Consequently, the accuracy and uncertainty are related, and it is important to conduct an uncertainty analysis that considers all sources of variability that could affect the results (Maroto *et al.*, 2000).

According to table 1, some land covers have a higher degree of uncertainty than others, which can affect the results of the DEM accuracy assessments. In this regard, when performing uncertainty analysis, category 6 forests are important to identify. Data collection for this cover type is more difficult because of the different heights of the individual trees and the varying cover density and/or size of the tree canopies, among other factors, which complicates the generation of reliable data. These problems occur for all types of remote sensors.

TABLE 2 shows that it is difficult to perform an optimal assessment of uncertainty of DEMs for

TABLE 1 Classification of land cover according to the Corine land cover method adapted to Colombia for the identification of uncertainty in DEMs.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Classification	Cover characteristics: Corin codes	Uncertainty
1. Artificial terrain	111, 112, 121, 122, 123, 124, 125, 131, 132, 141, and 142	Low
2. Temporary crops	211, 212, 213, 214, and 215	Low
3. Permanent crops	221, 222, 223, 224, and 225	Low
4. Pasture/grasslands	231, 232, and 233	Low
5. Heterogeneous agricultural areas	241, 242, 243, 244, and 245	Medium
6. Forests	311, 312, 313, 314, and 315	High
7. Areas with herbaceous and/or shrub vegetation	3211, 3212, 3221, 3222, and 323	Medium
8. Open areas with little or no vegetation	331, 332, 333, 334, and 335	Low
9. Wetlands	411, 412, 413, 421, 422, and 423	High
10. Open water	511, 512, 513, 514, 521, 522, and 523	High

TABLE 2 Landforms and slope gradient: Classification of IGAC for the identification of uncertainty in DEMs.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Simple forms	Complex forms	Slope gradient (%)	Symbols	Uncertainty
Nearly level	None	< 3	a	Low
Gently inclined	Undulating	3–7	b	Low
Moderately inclined	Rolling or slightly dissected	7–12	c	Medium
Strongly inclined	Strongly rolling or moderately dissected	12–25	d	Medium
Slightly steep	Strongly dissected	25–50	e	High
Moderately steep	Moderately ridged	50–75	f	High
Very steep	Strongly ridged	> 75	g	High

some gradients. Some terrains should be omitted by default because of their difficult accessibility, as these terrains are problematic for both remote sensors and field work. In these cases, it is recommended that sites with slopes with steep gradients of 25–50% (symbol e), 50–75% (symbol f), and > 75% (symbol g), which correspond to slightly steep to strongly ridged, be excluded or assigned the maximum uncertainty during the assessment.

In TABLE 3, an approach for qualitatively scoring the uncertainty associated with terrains of different slopes and land covers is presented. The uncertainty is categorically scored as high, medium, and low; the latter category presents the most favorable conditions for the DEM assessment.

3.3 Access to sources of higher accuracy

The technical Colombian norm NTC 5205, 'Precision of Spatial Data' (Precisión de datos espaciales), (Icontec, 2003) indicates that to estimate the accuracy of digital geospatial data sets, a source of data that is independent and separate from the data used in aerotriangulation or that is generated

TABLE 3 Uncertainty associated with terrains of different slopes and cover types.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Land Cover	Slope	Terrain
High	High	High
Medium	High	High
Low	High	High
High	Medium	High
Medium	Medium	Medium
Low	Medium	Medium
High	Low	High
Medium	Low	Medium
Low	Low	Low

by other procedures of greater accuracy should be used. The utilized data source should also be accessible and viable for evaluating the quality of the data set in question.

In evaluating the accuracy of the DEMs, researchers have mainly relied on three sources of data to obtain the reference elevation data: 1) DEMs of higher accuracy obtained from LIDAR, radar, and photogrammetric technologies; 2) digitized contour lines and rapid data collection techniques that satisfy the quality requirements of the product (Vílchez, 2000); and 3) ground control points (GCPs) established by a differential global positioning system (DGPS) and high-precision topographic surveys. The reference data in the quality assessment of cartographic products are better known as 'sources of higher accuracy'.

To adequately determine the most reliable sources for the accuracy assessment of a DEM, the following points should be considered:

The reference data used to conduct the assessment of a DEM should be, at a minimum, three times more accurate, and the data quality should be confirmed beyond a reasonable doubt.

The costs and errors should be known a priori in addition to the confidence level associated with the data sources of high accuracy.

The distribution of the check points should preferably be random for each stratum to guarantee data independence.

The source of higher accuracy should cover 100 % of the DEM to be evaluated; in contrast, it is necessary to indicate the coverage of the source of higher accuracy.

The distinct components (temporality, attributes, and so on) of the more accurate source to be used in the accuracy assessment of a DEM should be known.

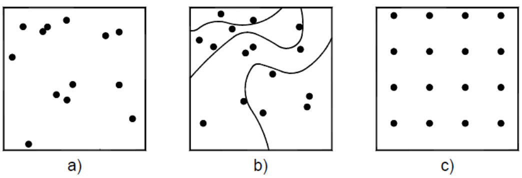
The sources of greater accuracy should be unrelated and external to the processes (different technologies, working groups, and so on) of the DEM to be evaluated.

3.4 Selection of the type of sampling

The type of sampling depends on the selection of the spatial units that form the basis of the accuracy assessment. The main recommendation is to use a probabilistic sample design, which is defined in terms of the probabilities of inclusion or, in other words, the probability that a given unit is included within the sample (Stehman, 2000). Several types of probabilistic designs are commonly applied during the accuracy assessments (FIGURE 3).

Specifically, the most common sampling methods applicable to the quality assessments of geographic information according to NTC 5660 (Icontec, 2010) are random, stratified Random, and systematic sampling (Wickham *et al.*, 2010).

FIGURE 3 Schemes for a) random, b) stratified random, and c) systematic sampling.
SOURCE: NTC 5660 (ICONTEC, 2010) AND ARIZA (2013)



Similarly, the selection of the type of sampling design should be based on the availability of information (Ariza, 2013). In the case of heterogeneous, mutually exclusive regions or nonoverlapping regions that do not cover an entire population, such as, for example, regions derived from an uncertainty analysis of the terrain, the use of stratified sampling is recommended.

3.5 Determination of the sample size

After defining the strata, the sample that is finally converted into a fixed characteristic of the design is selected. The analysis depends on the weight estimate that is associated with each sampling unit, which is determined by the sampling design. The impact of the strata selection is also reflected in the standard errors of the estimates (Wickham *et al.*, 2010).

The technical Colombian norm NTC 5660 (Icontec, 2010), 'Quality Assessment: Process, and Measurements' (Evaluación de la calidad. Proceso y medidas) establishes that the sample size should be proportional to the population size. In addition, in uncertainty analysis, a division of the terrain in subregions (strata) of uncertainty is generated, and thus, the sample size should be determined as a function of the uncertainty of each stratum. The following formula proposed by Cochran (1977) can be used to calculate the sample for a stratified random sampling (equation 1):

$$n = \left[\frac{\sum W_i S_i}{S}\right]^2 \tag{1}$$

where is the sample size, is the proportion of the area that belongs to subregion *i* (where $W_i = A_{R,i} \div A_{tot}$, A_R, is the area of subregion *i*, A_{tot} is the total area of the region evaluated in the DEM), S_i is the standard deviation of subregion *I*, where $S_i = \sqrt{P_i Q_i}$ and $Q_i = (1 - P_i)$ is the expected probability of accepting an elevation of high accuracy, and is the probability of accepting an elevation of low accuracy. For example, subregions of high accuracy would have a that is close to or equal to 0.5, whereas subregions of low accuracy would have a that is close to 1 while considering, the permissible standard error of the general vertical accuracy of the DEM, which is 0.25 times greater than the basic interval required for contour lines according to Resolution 64 of IGAC in 1994 (IGAC, 1994).

A sufficiently large sample is necessary to have a small standard error in the accuracy estimation of each stratum at a 95% confidence level. As a general rule, a minimum of 20 points is required; these should be distributed to reflect the geographic area of interest and the error distribution of the data according to NTC5205 (Icontec, 2003). In this regard, the distribution of the entire sample should be proportional to the area of each subregion provided that a sample of more than 20 points corresponds with each subregion. In the case that one subregion does not comply with this condition, it is recommended that 20 points be assigned to the subregion and that the remainder of the sample be proportionally distributed among the other strata as a function of its area.

The justification of this suggestion is that, in general, the accuracy is a primary objective that can be controlled by performing accuracy estimates to guide the allocation of the sampling effort. However, one disadvantage is that the selection of a design solely based on accuracy estimates can be detrimental for estimates of global accuracy. Finally, the definition of strata can be necessary when the number of strata are limited; in this case, accuracy estimates should be obtained as estimates per subpopulation or stratum (Stehman, 2000).

3.6 Spatial distribution of the sample

In the Report to CT-148 of AENOR (Informe al CT-148 de AENOR), which was conducted by Ariza & Atkinson (2006), the authors highlight that the distribution of control points can limit the sampling. Under ideal conditions when the area to be evaluated is homogeneous, a well-distributed random sampling can be considered. With respect to the sample distribution, the following should be considered:

Only one point should be located per pixel, and the minimum separation distance between points should be greater than the diagonal pixel size of the evaluated DEM. Similarly, for DEMs that use a floating marker for the accuracy assessments, the experience and visual sensitivity of the photogrammetrist should be accounted for, because this aspect will determine whether the floating marker is above or below the model surface and will influence the accuracy.

The check points should be separated by a sufficient distance to minimize the effect of the spatial autocorrelation given that, in contrast, the sample independence cannot be assumed (Congalton & Green, 2008).

3.7 Reliability and validity measures

The validation of the vertical accuracy of the DEMs has been considered in several studies; however, there is a lack of clarity with respect to the errors that are presented (Guo-an *et al.*, 2001). In effect, researchers have used different statistics to validate the quality of the obtained models. According to Quesada & Marsik (2012), the reliability and accuracy of the results of a DEM are linked with the inherent errors of the DEM; in other words, in general, errors are linked to the original data and processes used to generate the DEMs. For this reason, DEMs are validated while considering DEMs of greater accuracy or by GCPs and floating markers, among other methods.

Different researchers have evaluated the accuracy of DEMs using methods of exploratory analysis, including the calculation of quantiles, minimum values, maximum values, histograms and confidence intervals, dispersion (standard deviation and covariance), estimators (root-mean-square error, RMSE), mean arithmetic error, mean error (ME), mean absolute error, linear relationships (correlation coefficients), and comparison tests (Shapiro-Wilk).

In particular, the RMSE is a global measure that provides several advantages related to its ease of calculation and simplicity of use, and it is well-known. However, Droj (2008) recommends using other statistics, such as standard deviations, to verify the obtained error. In other research exercises, such as that developed by Hobi & Ginzler (2012), it is mentioned that it is common to find data extremes in data sets; accordingly, many data sets do not follow a normal distribution. Thus, these latter researchers suggest using robust statistics for data analysis. Similarly, Höhle & Höle (2009) recommend the use of robust statistics to determine the data accuracy, including those for evaluating data asymmetry or kurtosis.

4. Results

In the present study, the required inputs for the process of evaluating the vertical accuracy of the DEMs were identified, including data from articles, books, and open-access scientific databases as well as journals and books of the Center for Documentation (Centro de Documentación) of IGAC based on the expertise of professionals, working groups, and experts in the subject matter and on existing norms (ISO, NTC, and internal resolutions of the IGAC).

Initially, to evaluate the vertical accuracy of the DEMs generated from different remote sensors, the following inputs are required: data sets that correspond to the DEMs to be evaluated (generated from aerial photographs, radar images, and LIDAR cloud data) and reference elevation data sets.

In addition to the criteria identified for evaluating and quantifying the errors present in DEM data sets, three main steps were defined: First, the level and inspection method must be defined. Second, the basis of the uncertainty analysis, such as the slope and cover, must be identified. Finally, the sample design must be determined.

Given these recommendations, a procedure based on a set of steps was established for evaluating the positional accuracy of the DEM data sets, which is described as follows: 1) First, a sampling protocol that defines the inspection levels, or the detail at which the quality of the product will be evaluated, must be determined. An uncertainty analysis must then be conducted based on the parameters that characterize the measured values (Schmid & Lazos Martínez, 2000). The sampling design must be determined based on the samples subjected to the quality assessment of the data set. According to NTC 5660 (Icontec, 2010), 'Quality Assessment: Processes and Measurements' (Evaluación de la calidad. Procesos y medidas), this approach includes the selection of the sampling plan, the selection of the sampling method, and the determination of the sample size. 2) In addition, a design protocol must be implemented based on sources of spatially and temporally representative reference data that can be used to validate each sample unit (control points should be considered to be *true*, which is to say measured without error with respect to the values of the evaluated DEM). 3) Finally, a coherent analysis should be conducted based on the sampling plan and response design protocols.

In the current application of the proposed method, a stratified random sampling was selected. The data inputs utilized in the method are as follows: 1) the DEM to be evaluated, which was obtained by radar interferometry from P-band data (85 cm wavelength) generated by a GeoSAR sensor at a spatial resolution of 5 m with a vertical accuracy of 5 to 10 m and orthometric heights referenced to the geoid EGM96; 2) the reference DEMs obtained from photogrammetric processes with a spatial resolution of 5 m, a controlled accuracy of 1.5 m, and orthometric heights referenced to the geoid Geocol 2004 (IGAC, 2004); 3) the orthophoto mosaic of Cali at a scale of 1:5000 generated from aerial photographs taken in 2007 by a Vexcel Ultracam-D camera with a spatial resolution of 0.30 m and a spectral resolution of 3 bands; and 4) the land cover layer of Colombia at a scale of 1:100000, obtained by the Corine land cover method for the 2007-2010 period based on Landsat 7 images taken in 2007.

Finally, a slope map and land cover map for 2005-2007 were generated. To each of these categories, a degree of uncertainty that corresponds to low, medium, or high was assigned (FIGURE 4).

Additionally, a layer was created for the recategorization of uncertainty to proceed according to the sample design. In the present case, a stratified random sampling was used, and 62 random points were defined (FIGURE 5).

Therefore, the input values at each point were summed, and the obtained statistical values are listed in TABLE 4.

In the same way, the results of the sampling design (TABLE 5) can be evidenced in the range of 90 % 95 % and 99 % reliability. Reflecting the consistency in each of the percentages. Equally in FIGURE 6 the sample design is reflected with the same percentages respectively.

Correspondingly, quantification and error analysis were used the Mean, the Standard Deviation, the Mean Square Error, the Confidence Interval, the Coarse Error, the Percentile Range and the Percentile. Next, in FIGURE 7, the Standard Deviation, Mean Error and Quadratic Mean Error are taken first. Where the red darts show outstanding data.

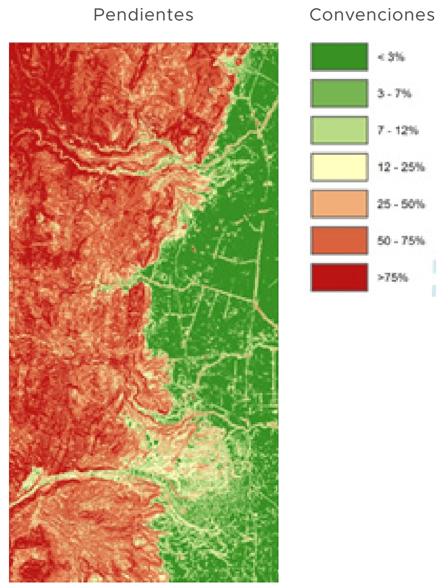
Finally, TABLES 6, 7 and 8 individually reflect the descriptive statistics and those of accuracy at 95 % confidence.

First, the Global uncertainty, in which the red data show the asymmetries of the accuracy statisticians.

FIGURE 4 Uncertainty associated with distinct land covers and slopes.

SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Simple forms	Slope gradient (%)	Uncertainty
Nearly level	< 3	Low
Gently inclined	3–7	Low
Moderately inclined	7–12	Medium
Strongly inclined	12–25	Medium
Slightly steep	25–50	High
Moderately steep	50–75	High
Very steep	> 75	High



Classification	Uncertainty
1. Artificial terrain	Low
2. Temporary crops	Low
3. Permanent crops	Low
4. Pastures	Low
5. Heterogeneous agricultural areas	Low
6. Forests	Medium
7. Areas with herbaceous and/or shrub vegetation	Medium
8. Open areas with little or no vegetation	High
9. Wet areas	High
10. Water bodies	High

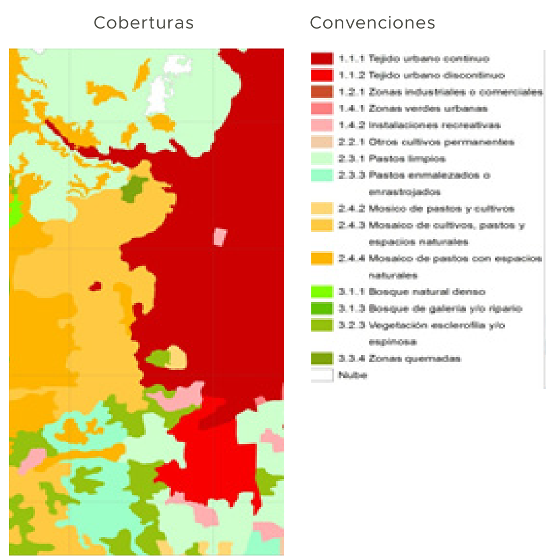
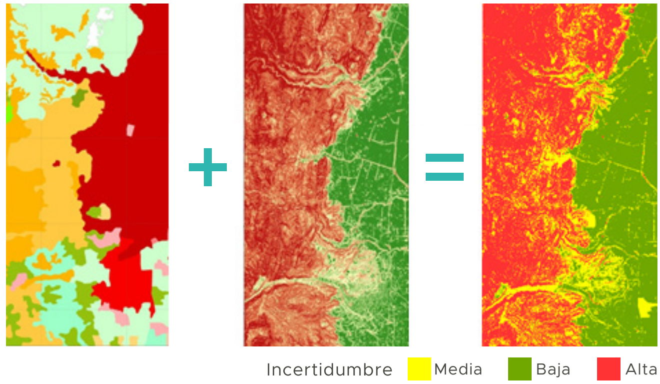


FIGURE 5 Final uncertainties for the study area.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Cover	Slope	Terrain
High	High	High
Medium	High	High
Low	High	High
High	Medium	High
Medium	Medium	Medium
Low	Medium	Medium
High	Low	High
Medium	Low	Medium
Low	Low	Low



	Area (ha)	wi	P	Q	Vi	Si	S	n	ni
High	9446	47%	70%	30%	0.21	46%	5%	62	29
Medium	4105	20%	80%	20%	0.16	40%			13
Low	6538	33%	90%	10%	0.09	30%			20
	20089	100%							62

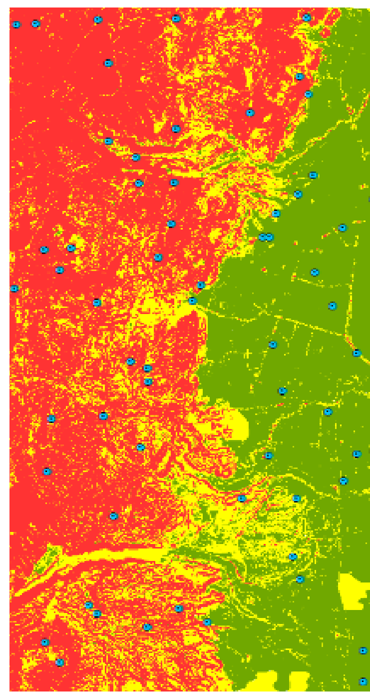


TABLE 4 Obtained statistics.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

	High	Medium	Low	Total
Sample	29	13	20	62
RMSE	4.30	3.18	2.61	3.59
Standard deviation	3.13	6.51	1.79	2.51
Mean	3.01	4.41	1.95	2.58
Confidence interval	8.14	15.09	4.89	6.70
Accuracy	7.05	5.21	4.29	5.88
Gross error	12.40	23.94	7.32	10.11

TABLE 5 Sample design.

SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

90 percent

ID	Uncertaintry	Area (Ha)	wi	pi	qi	vi	si	s	n	ni	ni (aj)
1	Low	6537.91	0.33	0.85	0.15	0.13	0.36	0.10	20	7	20
2	Medium	4105.44	0.20	0.65	0.35	0.23	0.48			4	20
3	High	9445.69	0.47	0.50	0.50	0.25	0.50			9	20
Total		20,089.04	1.00	N/A						20	60

95 percent

ID	Uncertaintry	Area (Ha)	wi	pi	qi	vi	si	s	n	ni	ni (aj)
1	Low	6537.91	0.33	0.85	0.15	0.13	0.36	0.05	81	26	26
2	Medium	4105.44	0.20	0.65	0.35	0.23	0.48			16	20
3	High	9445.69	0.47	0.50	0.50	0.25	0.50			38	38
Total		20,089.04	1.00	N/A						80	84

99 percent

ID	Uncertaintry	Area (Ha)	wi	pi	qi	vi	si	s	n	ni	ni (aj)
1	Low	6537.91	0.33	0.85	0.15	0.13	0.36	0.01	2014	655	655
2	Medium	4105.44	0.20	0.65	0.35	0.23	0.48			412	412
3	High	9445.69	0.47	0.50	0.50	0.25	0.50			947	947
Total		20,089.04	1.00	N/A						2014	2014

TABLE 7 summarizes the Mean Square Error between the global uncertainty, Low, Medium and High and **TABLE 8** with the summary of the Percentile Error that reflects the uncertainty e Global, Low, Medium and High.

5. Conclusions

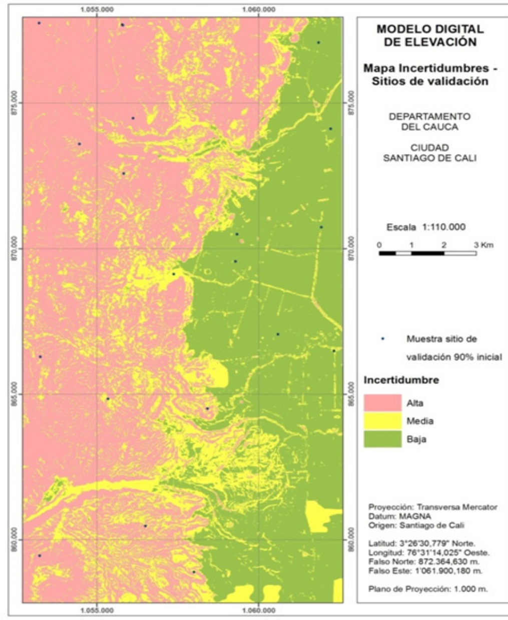
Digital terrain models (DTMs) contain several layers of information that represent distinct characteristics of the Earth's surface and are derived from elevational data calculated in DEMs. In particular, the vertical accuracy of a DEM is important depending on its intended use. However, the accuracy of the data sets used to elaborate such models are often unknown or not the same between data sets. Few studies have focused on the assessment of the error present in such models, and terrain analyses are often performed without quantifying the effects of the uncertainty. The method proposed herein is a new approach to the assessment of DEMs considering the geographic extension to be evaluated and the topographic characteristics.

The experimental results obtained in the development and testing phases suggest that it is appropriate to quantify the error of the DEMs using stratified RMSE tests. In contrast, the global RMSE, which is widely used, can mask the accuracy

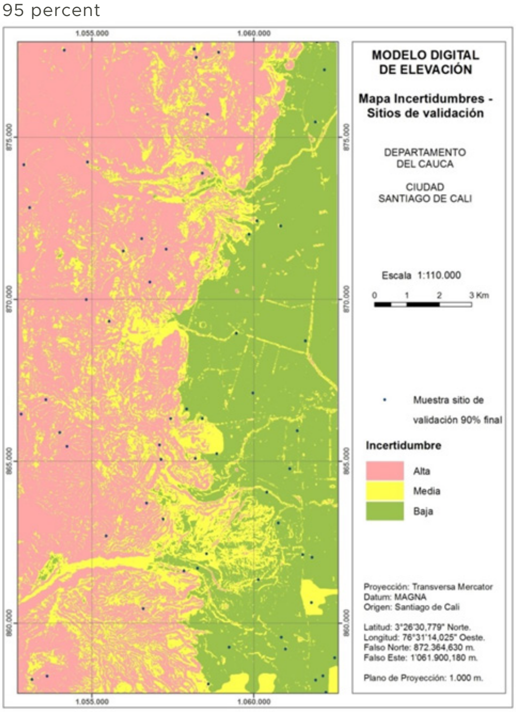
FIGURE 6 Sample Design.

SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

90 percent



95 percent



99 percent

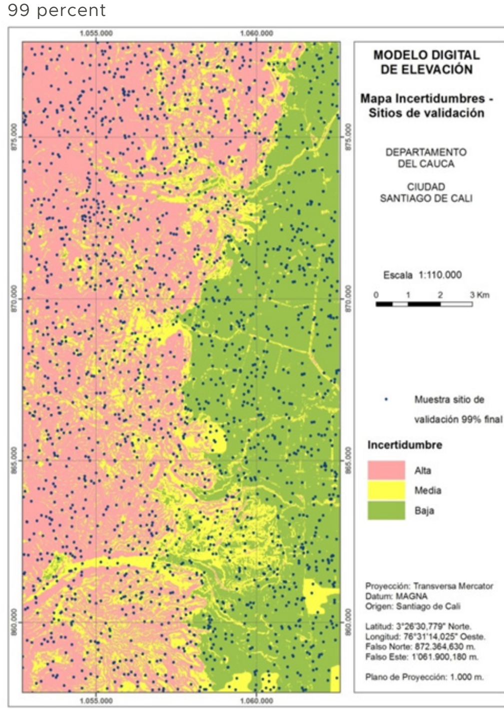


FIGURE 7 Quantification and error analysis

TABLE 6 Quantification and error analysis: Global Uncertainty al 95 %.

SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Descriptive Statisticians	Correlation	ASTER 2	STRM 3	STRM 4	Geosar X	Geosar P	Next Map W10	Next Map W30
Minimun	-3.31	-119.64	-25.24	-8.45	-3.01	-8.75	-19.88	-16.66
Maximun	17.29	77.67	45.77	23.86	21.83	16.21	25.48	27.56
Average	4.16	3.86	3.79	5.07	4.74	-0.05	3.08	5.08
Median	3.38	6.96	4.36	5.66	4.22	-0.34	3.20	5.13
Standard derivation	4.65	23.80	9.64	6.31	4.18	3.66	7.66	7.38
Median Deviation	3.25	8.25	3.87	3.17	2.31	1.67	4.77	3.53
Asimmetry	0.80	-1.57	1.01	0.22	1.53	1.32	0.14	0.11
Kurtosis	3.12	11.15	7.87	3.52	7.05	7.45	4.39	3.91
Coef. Var. Average (%)	111.73	617.02	254.57	124.50	88.20	-7604.08	248.60	145.30
Coef. Var. Median (%)	96.23	118.44	88.76	55.98	54.80	-260.83	148.76	68.77
Test Shapiro-Wilk								
Statiscal W	0.94	0.85	0.89	0.91	0.89	0.97	0.97	0.98
p-valor	0.00	0.00	0.00	0.00	0.00	0.08	0.19	0.22
Accuracy Statisticians								
Absolute mean error	4.59	16.29	7.28	6.63	4.91	2.55	6.15	7.09
Standard deviation	4.22	17.69	7.33	4.62	3.98	2.62	5.45	5.45
Error standard	0.46	1.93	0.80	0.50	0.43	0.29	0.60	0.60
Error thick	17.25	69.36	29.27	20.51	16.84	10.40	22.52	23.45
Error half square	6.22	23.97	10.30	8.07	6.30	3.64	8.19	8.92
Confidence interval	5.35	19.46	8.60	7.46	5.62	3.02	7.13	8.07
Accuracy	10.23	39.43	16.94	13.27	10.36	5.99	13.47	14.68
Percentile 95	13.10	43.56	19.41	17.00	10.13	6.80	17.46	16.60

TABLE 7 Quantification and analysis of error: Summary mean square error.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Uncertainty	NC	Correlation	ASTER 2	STRM 3	STRM 4	Geosar X	Geosar P	Next Map W10	Next Map W30
Global	90	5.00	26.16	6.62	5.99	4.14	3.11	7.32	7.73
Global*	90	7.56	16.19	7.33	7.05	5.14	2.63	4.90	6.82
Global*	95	6.22	24.60	10.03	8.64	6.30	3.47	8.18	8.87
Global*	99	6.64	34.69	9.02	10.55	5.95	3.81	7.79	8.74
Low	90	6.76	36.76	6.00	5.11	4.08	2.00	5.71	5.90
Low*	90	7.60	14.10	5.09	5.45	4.32	2.65	5.88	5.13
Low*	95	7.13	15.63	6.31	6.68	6.79	3.78	4.12	5.86
Low*	99	5.81	22.07	5.99	1.00	4.31	2.07	5.28	5.57
Medium	90	4.92	18.97	3.82	3.74	3.81	3.03	5.17	3.37
Medium*	90	5.59	14.29	7.09	6.42	4.52	2.26	6.04	6.19
Medium*	95	5.85	25.95	6.56	6.84	5.11	2.72	7.73	6.67
Medium*	99	7.75	30.97	8.36	9.7	5.84	3.24	8.11	8.65
High	90	3.05	24.24	11.37	7.35	4.42	3.81	8.76	10.14
High*	90	5.92	19.60	9.05	8.85	6.69	3.18	7.48	8.70
High*	95	5.72	28.66	13.13	10.48	6.52	3.60	9.70	11.27
High*	99	6.64	42.49	10.99	12.95	6.90	4.83	8.80	10.41

TABLE 8 Quantification and error analysis: Summary percentile error.
SOURCE: ELABORATED BY THE AUTHORS FROM IGAC DATA

Uncertainty	NC	Correlation	ASTER 2	STRM 3	STRM 4	Geosar X	Geosar P	Next Map W10	Next Map W30
Global	90	9.13	39.83	8.78	7.10	7.06	5.31	10.99	11.03
Global*	90	12.63	27.49	10.50	11.32	8.71	4.02	11.69	9.48
Global*	95	13.10	48.19	19.66	16.49	10.13	6.07	17.46	16.58
Global*	99	22.59	116.09	26.49	30.44	19.21	13.68	23.24	26.23
Low	90	10.19	63.13	7.80	6.66	6.01	2.62	7.80	8.10
Low*	90	12.64	22.78	8.45	8.45	7.45	3.53	8.18	7.53
Low*	95	14.1	21.39	9.37	10.28	9.32	5.77	7.14	9.02
Low*	99	19.05	75.43	16.75	15.96	11.94	6.51	14.57	14.84
Medium	90	7.37	26.58	5.48	5.63	5.57	4.19	6.09	4.26
Medium*	90	10.79	22.14	8.91	10.43	7.80	2.73	10.48	9.13
Medium*	95	12.53	47.39	12.09	12.09	8.75	5.21	12.99	14.15
Medium*	99	26.01	128.48	26.62	28.43	16.46	12.58	24.04	24.71
High	90	4.72	39.32	17.14	12.25	7.59	6.09	12.40	18.99
High*	90	9.58	28.99	14.49	15.00	9.88	5.50	12.36	14.38
High*	95	10.96	49.51	26.04	19.84	11.31	8.38	20.46	20.01
High*	99	23.10	184.27	31.34	38.82	22.60	16.53	24.73	30.03

of the data sets if atypical values or gross errors are present.

The analyses based on the reliability measures used during the development and testing phases of the present project are only valid if the errors present in the DEMs have a normal distribution. For this reason, it is necessary to verify whether or not the assumption of a normal data distribution is met.

The current methods for the assessment of DEMs are based on traditional statistics and assume hypotheses that are often not resolved or verified in practice. For example, it is often assumed that errors are normally distributed (or at least approximately normally distributed) or that the central limit theorem can be relied on to produce normally distributed estimates. Unfortunately, when atypical errors are present, the results by traditional methods are frequently of low quality. Therefore, it is necessary to identify and exclude these types of errors in the calculations.

It is further recommended that the identification and exclusion of gross errors present in the DEMs be performed with respect to the median, as this method gives a robust measure of central tendency, rather than with respect to the mean, which is a traditional measure of central tendency that is influenced by the presence of extreme values.

To validate the proposed method, additional tests with other data sets should be performed to identify potential problems and perform any necessary adjustments.

Finally, it is important to provide continuity to the development of the present project and to incorporate other aspects not considered in this first stage of development of the proposed method, such as other types of uncertainty that were identified during the analysis.

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