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Evaluation of digital land and geopotential models in Ecuador

Evaluación de los modelos digitales de terreno y geopotenciales en el Ecuador

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Abstract

Engineering uses digital elevation models to perform calculations and modeling phenomena, since it allows determining the scale at which they can be used and the quality of the by-products obtained. Two groups of models were evaluated, the digital terrain models (DTMs): Shuttle Radar Topography Mission (SRTM), ASTER Global Digital Elevation Map (ASTER GDEM), ALOS PALSAR and the DTM generated by the Instituto Geográfico Militar del Ecuador (IGM), and the geopotential models (GMs): EGM96, EGM08 and the GM created by the IGM. For the evaluation, the geometric leveling points and ellipsoidal height raised in one of the IGM projects were used to determine atypical values, calculate the mean square error (RMSE) and define the precision and scale at which the different ones can be used. The heights between the DTMs were compared to know their difference. It was determined that the SRTM 30, ALOS PALSAR and IGM DMTs can be used for jobs that require an accuracy of less than 10 meters. The GM EGM08 together with high precision ellipsoidal heights could generate elevation models that can reach an accuracy of 1.25 meters, while the GMs EGM96 and IGM can generate models that achieve an accuracy of 2.5 meters. The ellipsoidal heights of the SRTM 30, ALOS PALSAR and IGM DTMs obtained with the EGM 96 and EGM 08 GMs can only be used in jobs that require an accuracy of less than 10 meters.

Keywords: SRTM, ASTER GDEM, ALOS PALSAR, EGM 96, EGM 08, orthometric height, ellipsoidal height.

Resumen

Los trabajos de ingeniería utilizan los modelos digitales de elevación para realizar cálculos y modelar fenómenos, conocer su precisión permite determinar la escala de uso y la calidad de los subproductos que se obtienen. Existen modelos libres que son muy utilizados en la práctica, como es el caso de los modelos digitales del terreno (MDTs): Shuttle Radar Topography Mission (SRTM), ASTER Global Digital Elevation Map (ASTER GDEM), ALOS PALSAR, el MDT generado por el Instituto Geográfico Militar del Ecuador (IGM) y los modelos geopotenciales (MGs): EGM96, EGM08 y el MG creado por el IGM. Se evaluaron los modelos utilizando los puntos de nivelación geométrica y altura elipsoidal levantados por el IGM. Se determinaron los valores atípicos, se compararon las alturas entre los MDTs para conocer su diferencia, se calculó el error cuadrático medio (RMSE) y se definió la precisión y escala a la que se pueden emplear los diferentes modelos. Se concluyó que los MDTs SRTM 30, ALOS PALSAR e IGM pueden utilizarse para trabajos que requieran una precisión inferior a los 10 metros. El MG EGM08 junto con alturas elipsoidales de alta precisión podrían generar modelos de elevación que alcancen una precisión de 1.25 metros, mientras que los MGs EGM96 e IGM pueden generar modelos que alcancen una precisión de 2.5 metros. Las alturas elipsoidales de los MDTs SRTM 30, ALOS PALSAR e IGM obtenidos con los MGs EGM 96 y EGM 08 se pueden utilizar si se requiere una precisión inferior a los 10 metros.

Palabras clave: SRTM, ASTER GDEM, ALOS PALSAR, EGM 96, EGM 08

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1 Introduction

The characteristics of the terrain limit the activities that humans can perform; for this reason, engineering analyzes the characteristics of the terrain and determine the accuracy the models require to conduct the studies. For example, civil engineers analyze the land before building, geomorphologists understand the shape and processes that gave rise to it, surveyors measure and describe the land surface. There are different digital models that can be used depending on the vertical reference system required for the study. The digital terrain models, known as MDT, have their heights referring to the natural characteristics of the territory under study. While digital surface models, known as MDS, refer to their heights above the ground (Li et al., 2004).

The importance of having high-quality digital elevation models lies in the large number of applications that exist. Agriculture (Sinde-González et al., 2021), civil works (Abbondati et al., 2020), archeology (Peña Villasenín et al., 2017; Gil-Docampo et al., 2023), environmental management (McClean et al., 2020) or territorial planning (Zafar and Zaidi, 2019), among others, are among the most current and require more precision. However, on a planetary scale, centimeter-level precisions are not required and therefore global models are used. In this case, the applications focus on studies of geodynamics (Luna et al., 2017) and geodesy (Orejuela et al., 2021).

The definition of the SIRGAS Vertical Reference System is identical to the definition of the International Height Reference System (IHRS). Both point out the importance of using physical heights for conducting engineering works (Sánchez, 2015). Orthometric height is the most used physical height and is obtained by dividing the geopotential dimension for a mean gravity value (Drewes et al., 2002). Geoidal undulation depends on the ellipsoid used, but its variability is approximately within *pm* 100 (m) (Seeber, 1993). As known, GNSS positioning provides high-precision ellipsoidal heights efficiently, but to obtain high-precision orthometric heights it is necessary to generate high-precision MGs (Martínez and Bethencourt, 2012).

1.1 MDT Shuttle Radar Topography Mission (SRTM)

It was created by an initiative of the National Aeronautics and Space Administration (NASA), the German Aerospace Center, DLR, and the Italian Space Agency, ASI. It is an MDT with two resolution levels, one of 1 (30 meters) and another of 3 seconds of arc (90 meters), which covers 80 % of the earth's surface from the 60° north to the 57° south. The horizontal accuracy of the MDT is greater than $\pm$ 20 (m), while the vertical accuracy meets $\pm$ 16 (m) for 90 % of the data across the mission (Rabus et al., 2003). The type of height of the MDT SRTM is orthometric, since the MG EGM 96 was used to transform the ellipsoidal heights (Lemoine et al., 1998).

1.2 MDT generated by the Military Geographic Institute (IGM)

It was generated from the curve level obtained by restitution of the mapping generation project 1:5 000. These curves were generalized and interpolated to obtain a TDM with a resolution of 30 (m). The type of heights of the IGM MDT is orthometric generated with the MG EGM96 and its use is recommended for generating cartography 1:50 000.

1.3 MDT ASTER GDEM

Obtained by NASA and METI efforts in mid-October 2011. This model covered the Earth's surface from the 83° north to the 83° south. Its spatial resolution reached 1 second of arc (30 meters) and the vertical precision is around 20 meters with a confidence level of 95 %. The orthometric heights of the MDT ASTER GDEM were obtained by using the MG EGM 96 (Tachikawa et al., 2011).

1.4 MDT ALOS PALSAR RTC

Distributed by Alaska Satellite Facility (ASF), it converted the orthometric heights of SRTM or NED MDTs into ellipsoid heights using the ASF MapReady geoid_adjust tool. This tool applies a geoid correction so that the resulting MDE is related to the ellipsoid (Alaska Satellite Facility, 2021).

Table 1 details the technical characteristics of the TDMs used in the research.

Table 1. Technical characteristics of the MDTs.

MDT	Vertical Accuracy	Spatial resolution	Height type
SRTM	± 16.0 m	30 m	Orthometric
IGM	± 12.5 m	30 m	Orthometric
ASTER GDEM	± 20,0 m	30 m	Orthometric
ALOS	-	30 m	Ellipsoid

1.5 MG EGM 96

It has a spatial resolution of approximately 56 kilometers, incorporating surface gravity data, ERS-1 and GEOSAT Geodetic Mission gravity anomalies, position and altimetry satellite data from various systems. The model is defined up to 360 degrees, allowing to calculate 131000 harmonic coefficients (Lemoine et al., 1998).

1.6 MG EGM 08

It has a spatial resolution of approximately 9 kilometers. It was developed by the combination of least squares of the ITG-GRACE03S gravitational model and its error covariance matrix. For its generation, gravitational information was extracted from a 5-minute-of-arc equiangular grid. This set of gravity anomalies was obtained by merging data from ground and airborne sensors with values derived from altimetry. The least squares adjustment was performed in terms of ellipsoidal harmonics; this conversion retained the order but not the degree, originating coefficients of grade 2190 and order 2159 (Pavlis et al., 2012).

1.7 MG generated by IGM

It used GPS techniques and geometric leveling to structure and train an artificial neural network of the type Radial Basis Functions (RBF) that allows calculating the geoidal undulation at any point by interpolation Tierra Acurio, 2014).The MG of the IGM obtained errors less than 40 cm and a mean quadratic error of 15 cm (Tierra and Acurio, 2014).

Engineering requires that the models and cartographic products meet a certain precision, not knowing the accuracy can cause economic and logistic problems. The TDMs and GMs used in this research, except for the TDM and the GM generated by the IGM, have been generated worldwide and have scientific literature that supports their accuracy worldwide, but has this accuracy been met in Continental Ecuador? In this way, the aim is to determine the accuracy of the models and the maximum scale at which they can be implemented for elaborating cartographic products in Continental Ecuador.

2 Materials and methods

The data used can be observed in Figure 1: one of the four MDTs and the points of geometric leveling and ellipsoidal height raised in one of the IGM projects. Although it is true that the geometric level heights would not be useful to evaluate the orthometric heights of the physical MDTs, it was determined by previous evaluations of the MDTs presented in the introduction that the accuracy of the MDTs reaches 15 meters, and as in the Continental Ecuador it has been determined that the difference between the level height and the orthometric height reaches the meter (Cañizares, 2015).

In addition, in the present investigation the difference between level height and orthometric height was rejected, since the accuracy of the MDTs would absorb the difference. There were points with ellipsoidal height that served to evaluate the transformation of orthometric heights of the MDTs in ellipsoidal heights and a pseudo geoidal ripple was calculated to evaluate the MGs at the points where the data had the level height and ellipsoidal height.

The equation of physical geodesy (Equation 1) considers geoidal undulation (N) as the vertical separation between the ellipsoidal height (h) and orthometric height (H). This consideration is used because of the ease of transforming the ellipsoidal heights into orthometric and vice versa, thus avoiding using gravimetric models and gravity measures to obtain physical heights, which make the costs of the projects more expensive.

$$N = h - H \tag{1}$$

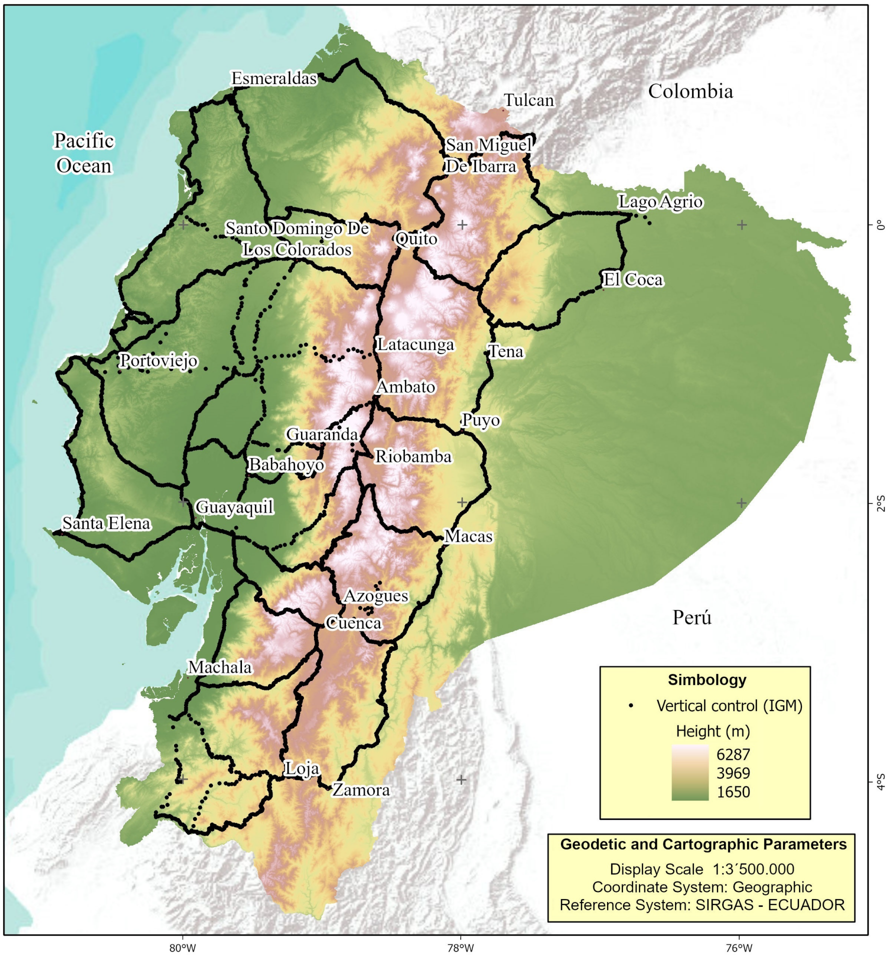

Figure 1. Elements used for evaluating the MDTs and MGs.

A spatial table was generated to evaluate the different MDTs and MGs. For this purpose, the leveled and ellipsoidal elevation performed by the IGM was georeferenced. At each point of the survey, the height value present in each pixel of the different MDTs was extracted, without resorting to any interpolation method for the extraction, because each point of the survey was located within a single pixel.

The geographical coordinates of each point of the survey were calculated and the spatial table was transformed into a .dat file that served as input to calculate the geoidal undulations with the MG EGM 96, EGM 08 and IGM. Using ETL software, the geo-ideal ripples present in each of the .dat files were added to the spatial table of points. The geoidal pseudo-undulation was calculated with the Geographic Information System (GIS), for each point of the uplift where the level height and ellipsoidal height existed at the same time. Hence, Equation 1 was used, where the level height of the ellipsoidal height was subtracted.

Subsequently, the original orthometric height of the MDTs was evaluated. The orthometric heights of all models except for the MDT ALOS PALSAR were obtained by using the MG EGM 96. The original heights of the MDT ALOS PALSAR are ellipsoidal heights, reason for which equation 1 was used to transform the ellipsoidal heights into orthometric heights, using the MG EGM 96.

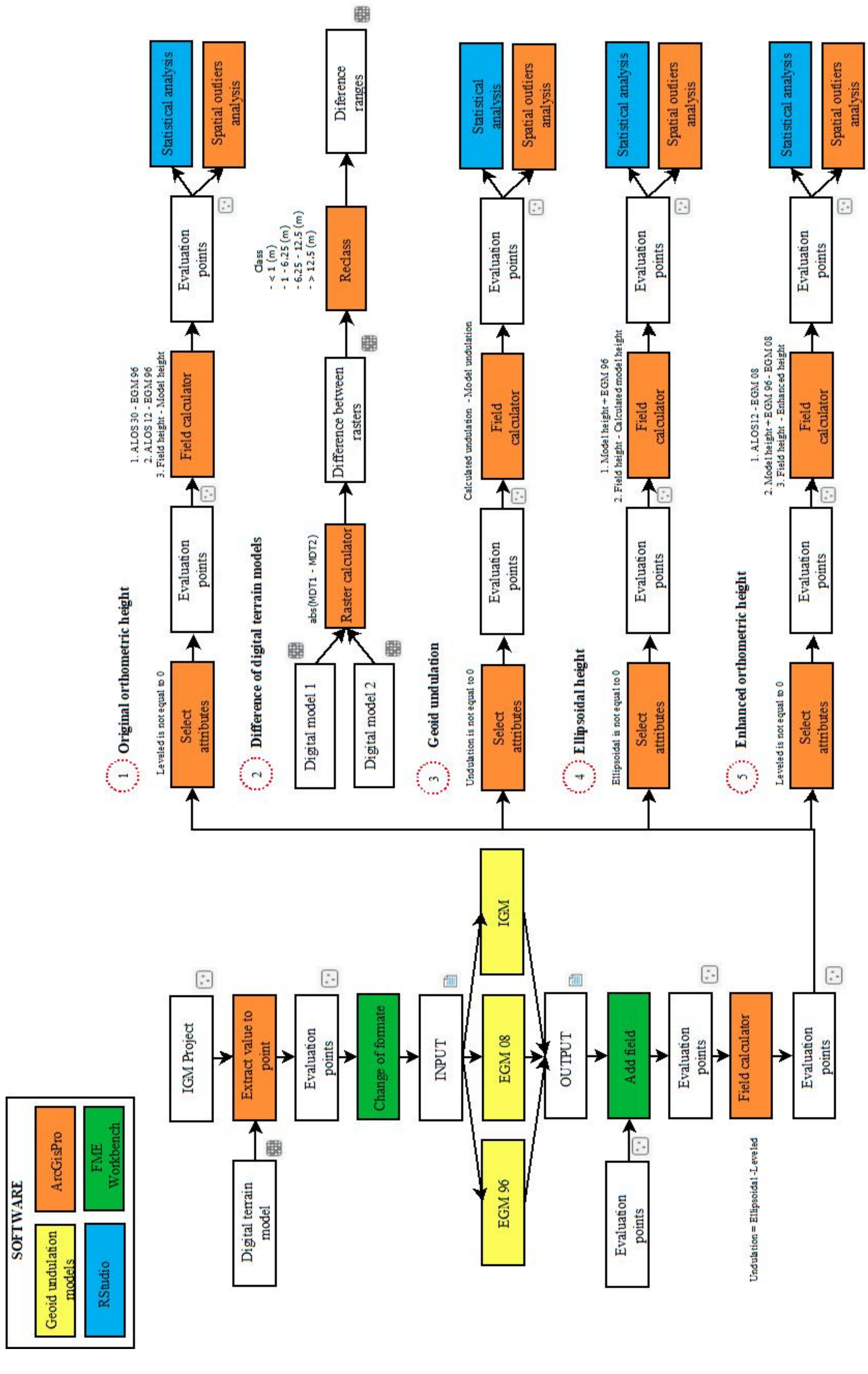

Figure 2. Mapping model for assessing TDMs and GMs.

Also, 3931 points were used, which had level heights of the IGM project to evaluate the vertical accuracy of the MDTs. It required calculating the difference of the captured value in the field with respect to the value of the MDT. Subsequently, it was proceeded to analyze the distribution of the differences with box diagrams, we plotted the dispersion of the differences with respect to the height at which the differences were calculated and calculated the RMSE of each BAT. The accuracy reported with the RMSE reflects all uncertainties, including errors in data acquisition, compilation and final calculation of heights (Federal Geographic Data Committee, 1998).

The differences were analyzed spatially using the local Moran´s I value in order to understand how the difference of a point is related to the differences that surround it, thus determining spatial clusters and atypical values (Anselin, 1995). The local Moran´s I uses a z-score, a pseudo-P-value to represent the statistical significance of the calculated index values. A negative value for I indicates that an entity has neighboring entities with different values; this entity is an outlier. In both instances, the P-value for the entity must be small enough for the outlier to be considered statistically significant. An outlier can be of two types, a high value surrounded primarily by low values (high - low) and a low value surrounded primarily by high values (low-high). Statistical significance is set at a 95% confidence level (ESRI, 2020).

Once MDTs were statistically and spatially analyzed, the second step was to determine the difference between each MDT. As mentioned, the MDT ALOS PALSAR has ellipsoidal heights, while the other MDTs have orthometric heights, reason for which no difference raster was generated with the MDT ALOS PALSAR. The differences raster served to classify the differences, visualize their spatial behavior, analyze the coverage percentage of each difference range and determine to what extent the DMTs can be considered similar to be able to use them together and overcome their weaknesses.

The MGs were evaluated, where 1253 points of the IGM project were used since they had the value of the geoidal pseudo-undulation. The difference between the geoidal pseudo-ripple captured in the field was determined with respect to the ripple calculated with the MGs EGM 96, EGM 08 and IGM model. Once with the calculated differences, the distribution of the differences was analyzed, the dispersion of the differences was plotted with respect to the height at which they were calculated. The RMSE of each model was calculated and the outliers were spatially analyzed using the local Moran´s I.

1253 points of the IGM project were used to evaluate the ellipsoidal height of the MDTs. For this reason, the orthometric heights of the MDTs SRTM, ASTER GDEM and IGM were transformed into ellipsoidal heights using equation 1 and the MG EGM 96. It was not necessary to transform the heights of the MDT ALOS PALSAR, because the original heights of the MDT are ellipsoidal heights. We proceeded to determine the difference between the ellipsoidal height captured in the field with respect to the ellipsoidal height of the MDTs, analyze their distribution, plot their dispersion with respect to the height at which the differences were calculated, calculate the RMSE and spatially determine the outliers using local Moran´s I.

The last step was to determine if using MG EGM 08 with the ellipsoidal heights calculated in the previous step could achieve MDTs of more accurate orthometric heights. In the 3931 points that had the level height of the IGM project, the original orthometric heights of the MDTs were transformed into ellipsoidal heights, using equation 1 and the MG EGM 96. Then the ellipsoidal heights were transformed into orthometric heights using again equation 1 and the MG EGM 08. As in the previous steps, the difference between the obtained value in field with respect to the value of the model was determined, its distribution was analyzed, the dispersion of the differences with respect to the height to which they were calculated was plotted, the RMSE was calculated and the atypical values were spatially determined using local Moran´s I.

3 Results

3.1 Evaluation of orthometric height with the MG EGM 96 of the MDTs

The distribution of differences was analyzed in the level heights captured in the field with respect to the orthometric heights of the MDTs obtained with the MG EGM 96. Figure 3 and 4 and table 2 show the influence of spatial resolution on the distribution of differences for models that have been distributed with two resolutions. In the case of the MDT SRTM, it is observed that the differences obtained with the 30-meter resolution model are better than the differences obtained with the 90-meter model, since they present a better grouping of the data, a narrowing and better location of the box. In the case of the MDT ALOS PALSAR, the differences between the 30-meter model and the 12.5-meter model are hardly identifiable since their boxes have the same size and are in the same position.

Table 2. Values of orthometric height assessment box diagram with MG EGM 96.

MDTs	Max	Q3	Med	Q1	Min
SRTM 90	13.58	1.32	-1.96	-6.94	-19.30
SRTM 30	14.22	4.92	1.61	-1.33	-10.56
ASTER	24.03	7.24	1.88	-3.99	-20.83
ALOS 30	10.95	1.48	-1.45	-4.88	-14.41
ALOS 12.5	10.59	1.46	-1.48	-4.70	-13.94
IGM	10.26	0.98	-1.81	-5.26	-14.58

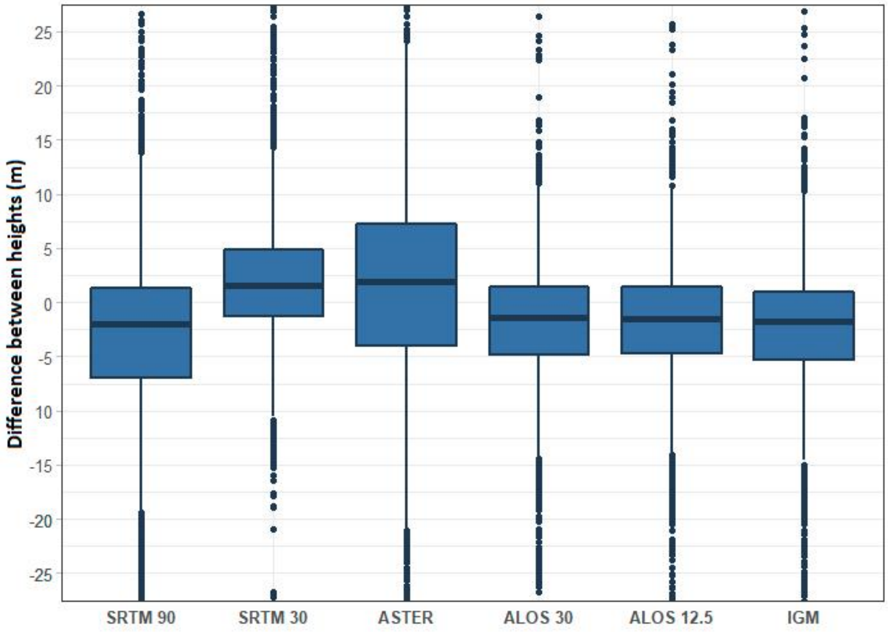

Figure 3. Orthometric Height Difference Box Diagram with MG EGM 96.

When comparing the box of all the MDTs, it is observed that the box of the MDT ASTER GDEM is the widest and therefore has the worst distribution of the differences; in turn, it is observed that the median of this model is similar to the median of the MDT SRTM of 30 meters. The ALOS PALSAR and IGM MDT boxes have similar statistical characteristics both in the width of the box and in its location. All boxes except the 90-meter SRTM model box show a similar data distribution both above and below the median value in the boxes, and to the right and left of the mean value, in the histogram (symmetry).

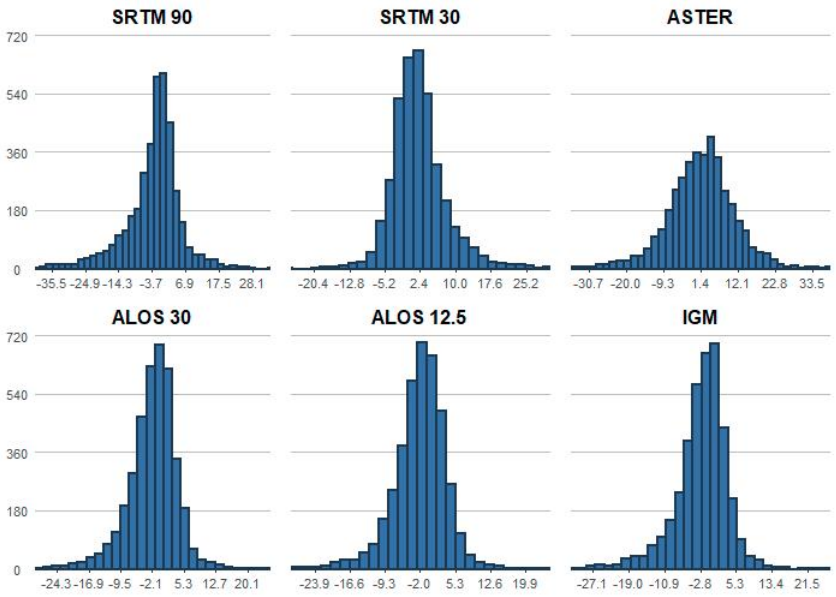

Figure 4. Histogram of orthometric height difference with MG EGM 96.

Figure 5 shows that the dispersion of differences regarding the height of the evaluation point is grouped around 0 meters, where MDTs SRTM 30 meters, ALOS PALSAR 30 and 12.5 meters and IGM tend to be better grouped than MDTs ASTER GDEM and SRTM 90 meters. It is observed that the 30-meter MDT SRTM has more positive differences, while the 90-meter MDTs SRTM ALOS PALSAR 30 and 12.5 meters and IGM tend to have more negative differences.

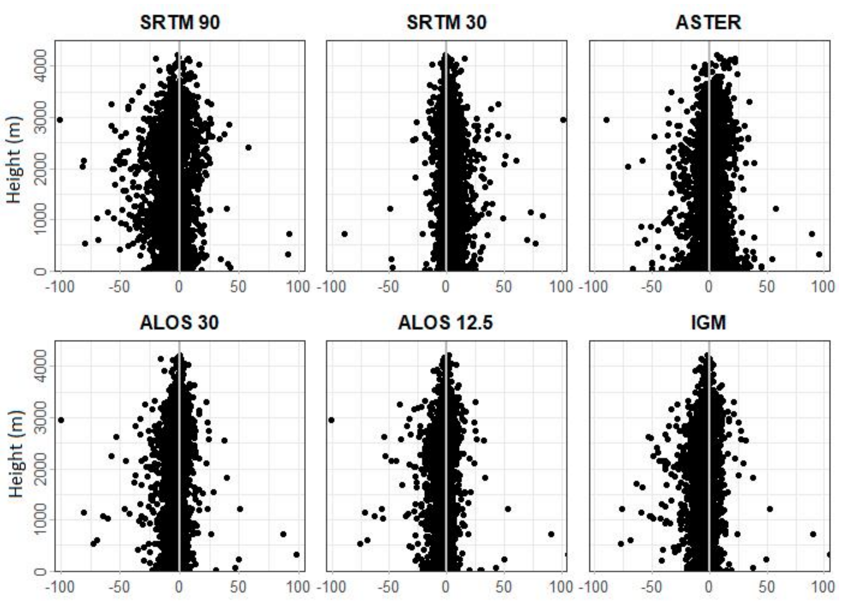

Figure 5. Dispersion of orthometric height difference with MG EGM 96.

A uniform distribution of differences is observed in all TDMs as the assessment height increases. Based on observations in Figure 3, Figure 4 and Figure 5. In addition, it was decided to choose the 30-meter MDTs SRTM and 12.5- meter ALOS PALSAR for the next steps of the evaluation, as they presented better statistical results.

In the spatial analysis of outliers with the local Moran´s I observed in the outliers. can be seen a similar behavior in the typology and location of outliers in the MDTs SRTM, ALOS PALSAR and IGM, where most of the outliers are present in the Andes. The MDT ASTER GDEM is characterized by having a considerable amount of differences with a high value surrounded by differences with a low value in the northeast of Ecuador. All TDMs had 3 % high-low outliers and 2 % low-high outliers.

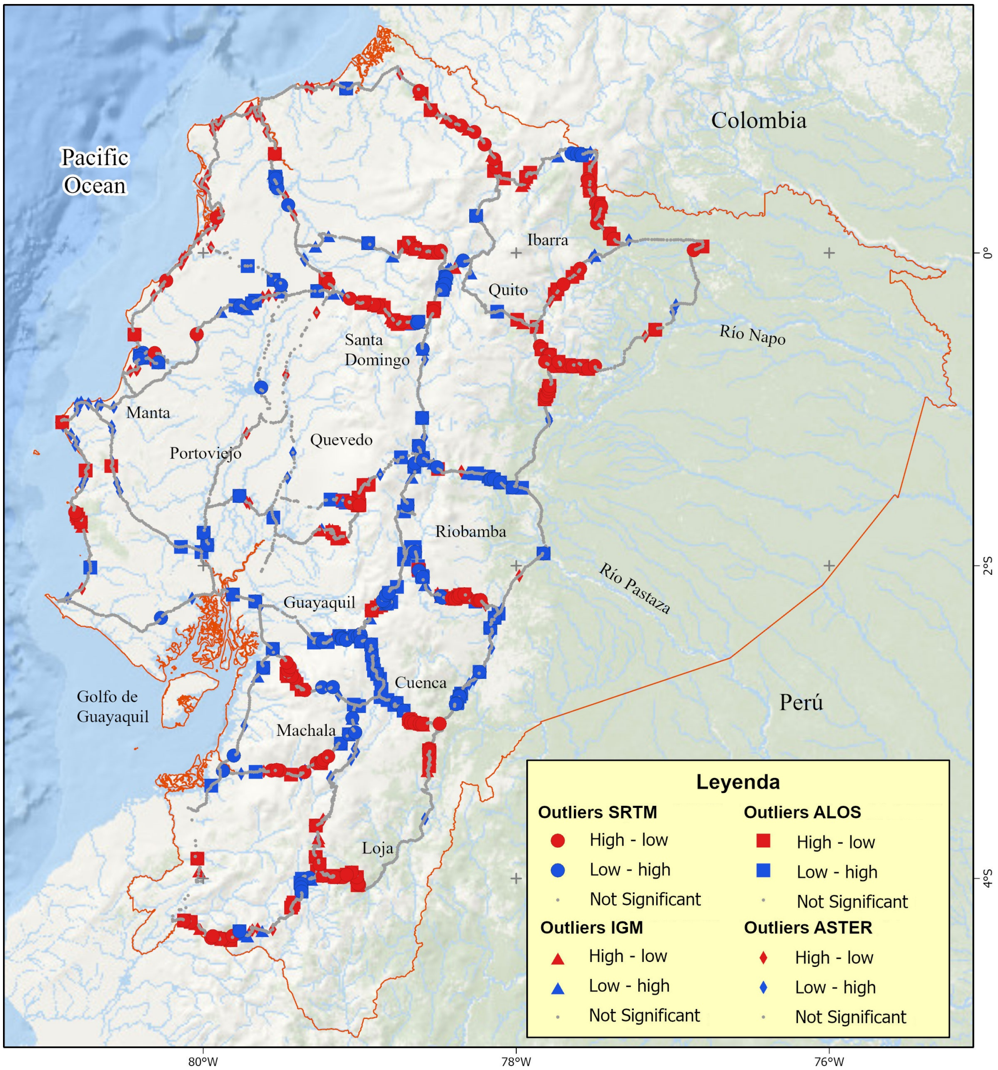

Figure 6. Outliers analysis of orthometric height differences with MG EGM 96.

The spatial distribution of the differences between the MDTs that had the original height at orthometric height was determined; for this reason, the MDT ALOS PALSAR was excluded from the analysis. The difference between IGM and SRTM MDTs is observed in Figure 7, where an area of high differences between the provinces of Sucumbíos and Orellana stands out. By analyzing the models separately, it was discovered that this difference is caused because the IGM MDT has zones that have a constant height value.

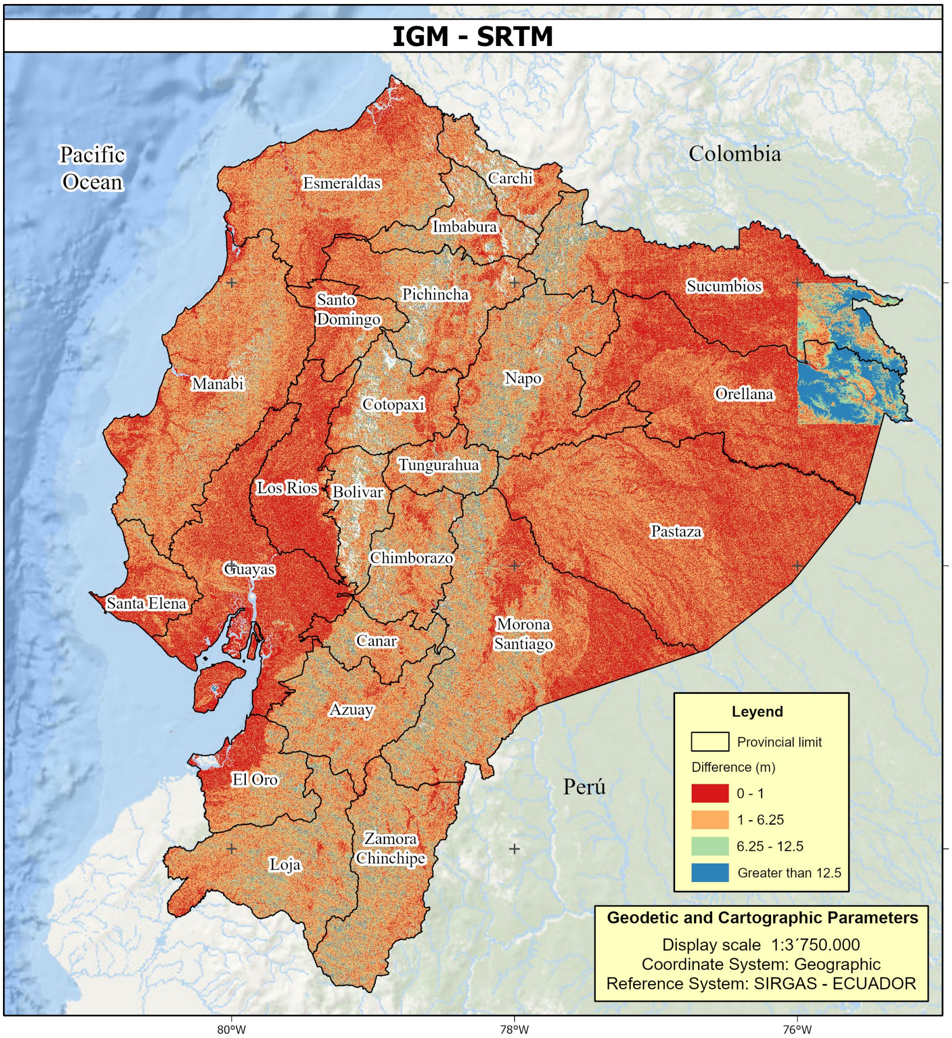

Figure 7. Difference between IGM and SRTM MDTs.

A bar chart was generated with the classification of differences between the MDTs to quantify what is observed in Figure 7. According to Figure 8, 96 % of the differences are lower than the tolerance of the scale 1:50,000 (12.5 meters), so it can be considered that these models can be complemented to fill their shortcomings. For example, the deficiency of the SRTM model covers 93 % of the continental territory, while the MDT IGM covers 100 %.

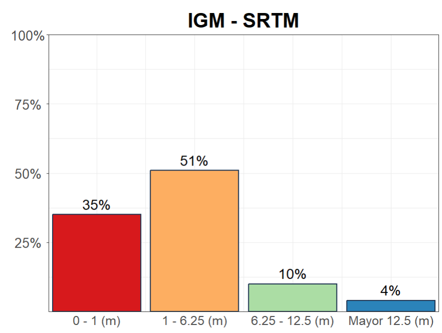

Figure 8. Difference bar diagram between IGM and SRTM MDTs.

Figure 9 shows that the tones that prevail in the map of differences between IGM MDTs and ASTER GDEM are in the ranges between 1 and 12.5 meters. The bar diagram in Figure indicates that 63% of the differences are in the range between 1 and 12.5 meters. Even though there is a considerable reduction in the percentage of differences that are less than the tolerance of the scale 1:50,000, only 70% of the differences are smaller.

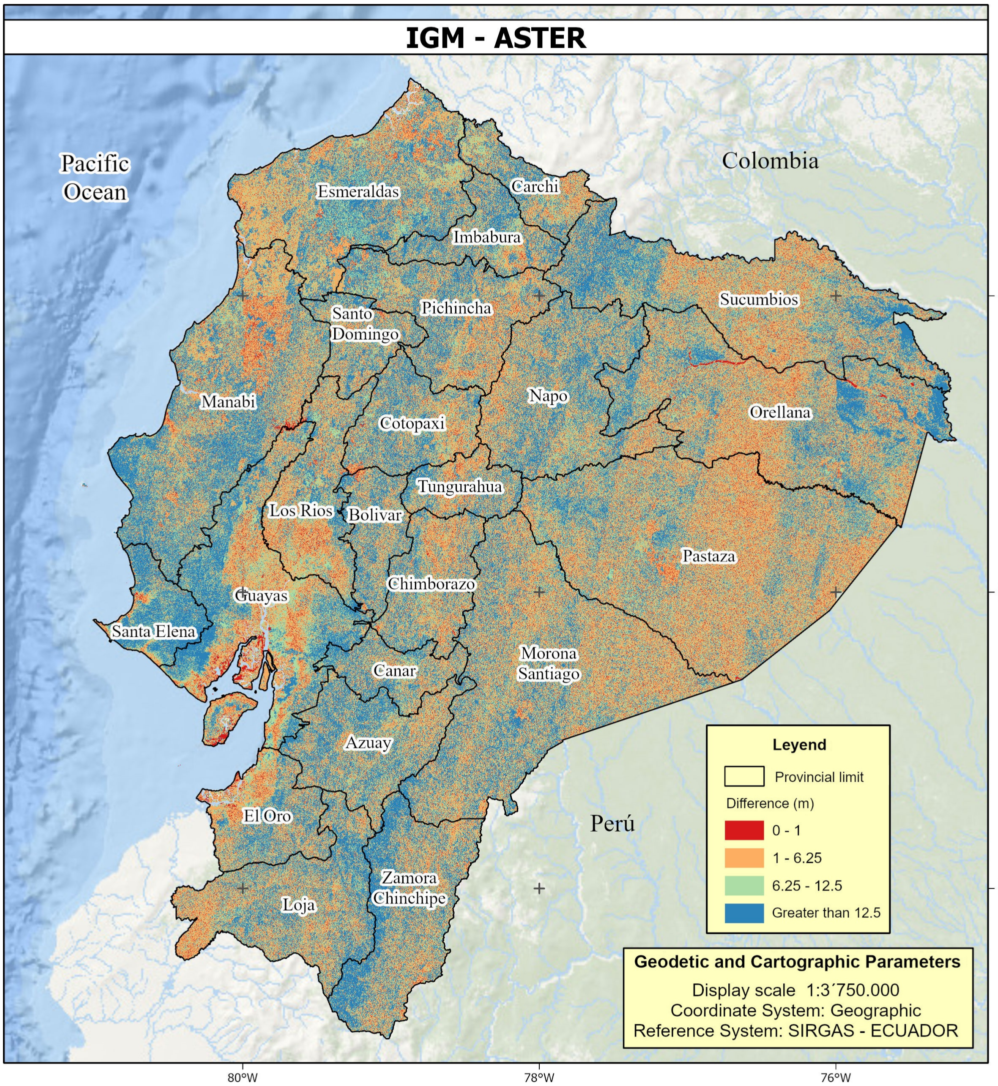

Figure 9. Difference between IGM and ASTER MDTs.

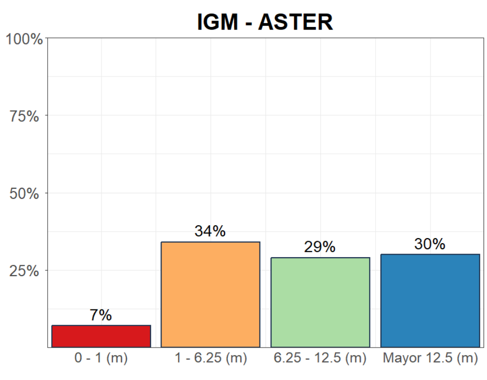

Figure 10. Difference bar diagram between IGM and ASTER MDTs.

A similar behavior is observed on the Difference Map of Figure and in the difference map of Figure . When analyzing the bar diagram of Figure , it is found that the behavior is the same, since the percentages of the differences ranges are equal to that of Figure. When the differences between IGM and SRTM MDTs were analyzed, a zone of high differences between the provinces of Sucumbíos and Orellana was observed. In Figure traces of that area are seen, while in Figure this area disappears.

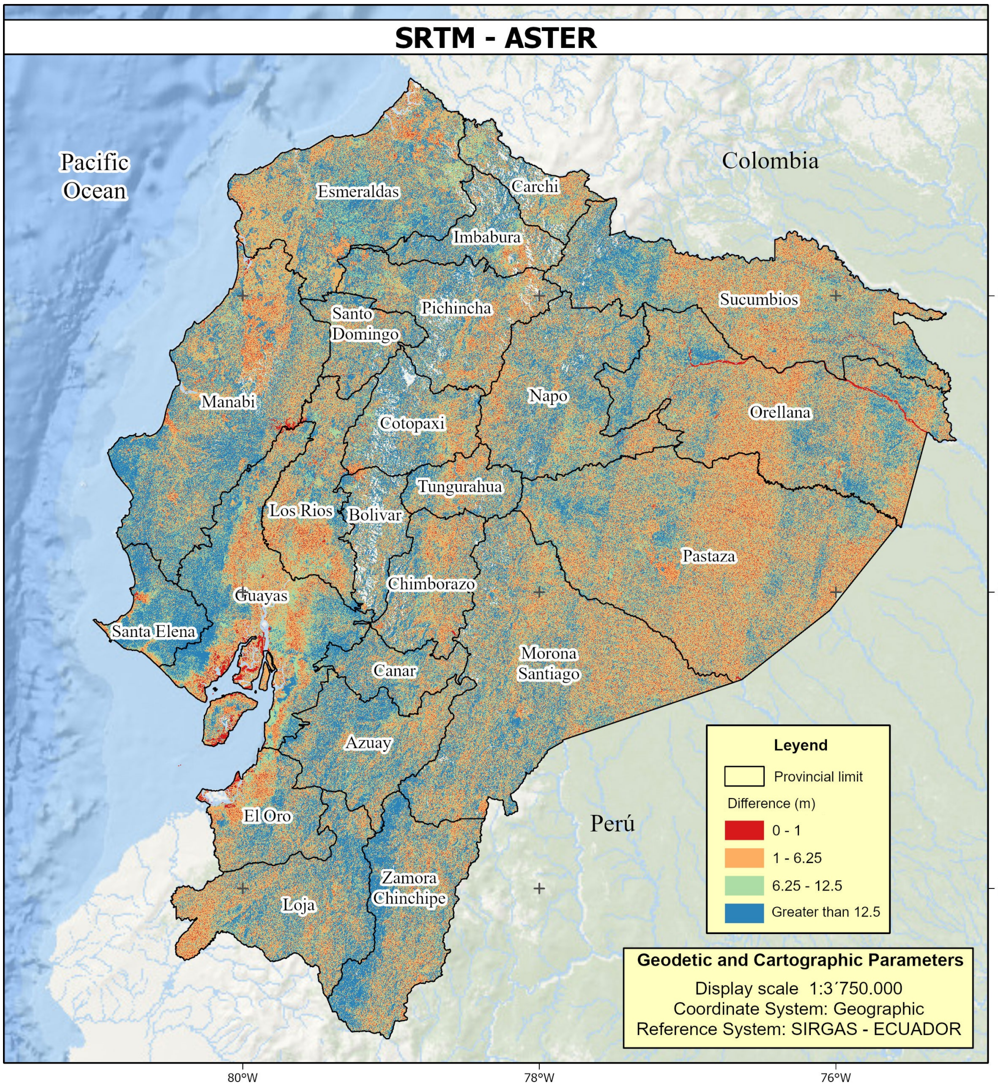

Figure 11. Difference between MDTs SRTM and ASTER.

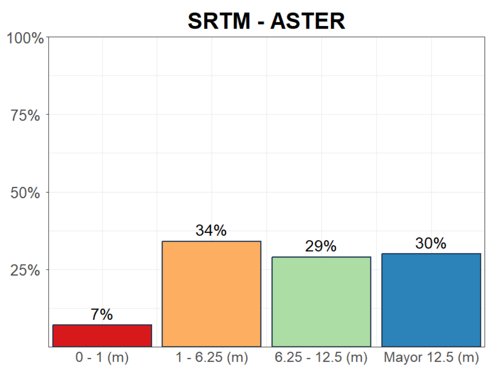

Figure 12. Difference bar diagram between SRTM and ASTER MDTs.

3.2 Evaluation of MGs

We analyzed the distribution of the differences between the geoidal pseudo-undulations calculated from the information captured in the field with respect to the geoidal undulations obtained from the MGs. Figures 13 and 14 and Table 3 show that the MGs box is symmetrical with respect to the median. MG EGM 96 has a similar median as MG EGM 08 and the MG IGM box has the smallest extent of all.

Table 3. Values of the MGs box diagram.

	EGM 08	EGM 96	IGM
Maximum	1.38	2.65	-0.12
Q3	0.29	0.59	-0.75
Median	-0.12	-0.12	-0.94
Q1	-0.47	-0.90	-1.17
Minimum	-1.48	-2.92	-1.81

Figure 15 shows the dispersion of the differences in the geoidal undulation with respect to the evaluation height, where the differences in the MGs EGM 08 and IGM tend to be better grouped around 0 meters. The MGs EGM 08 and IGM show a uniform distribution of differences as height increases, while the MG EGM 96 shows a high dispersion of difference between 500 and 2000 meters in height.

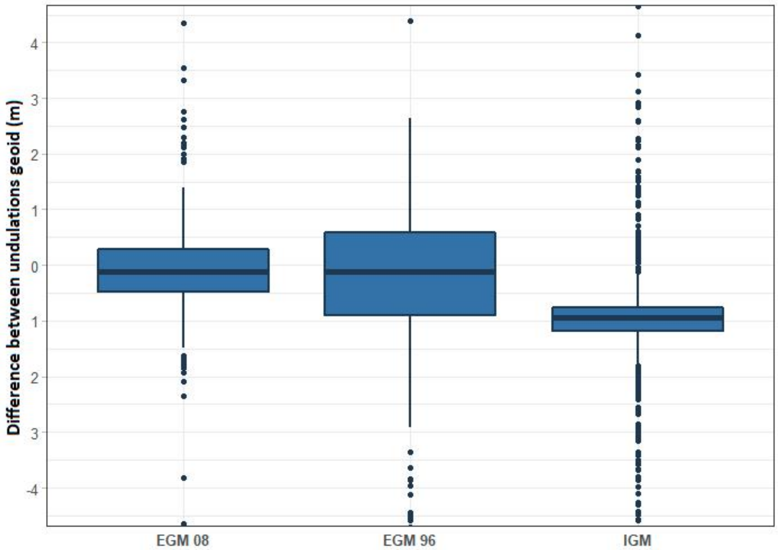

Figure 13. Boxplot diagram of the difference of MGs.

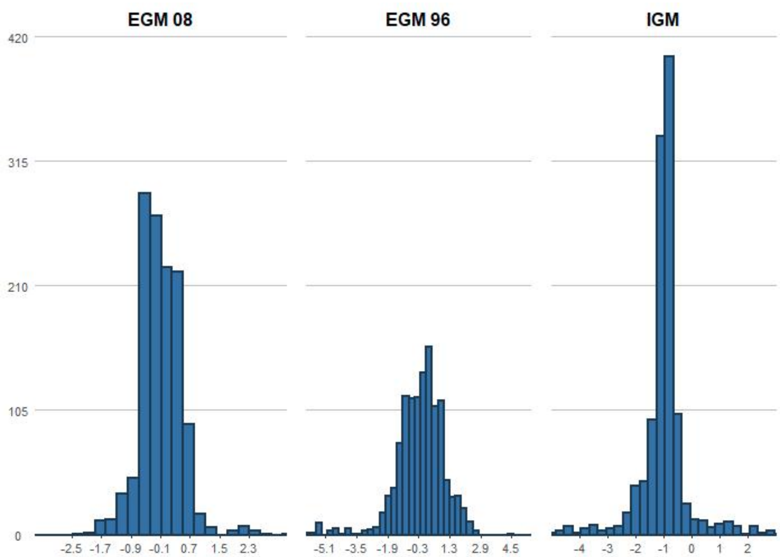

Figure 14. Histogram of MGs difference.

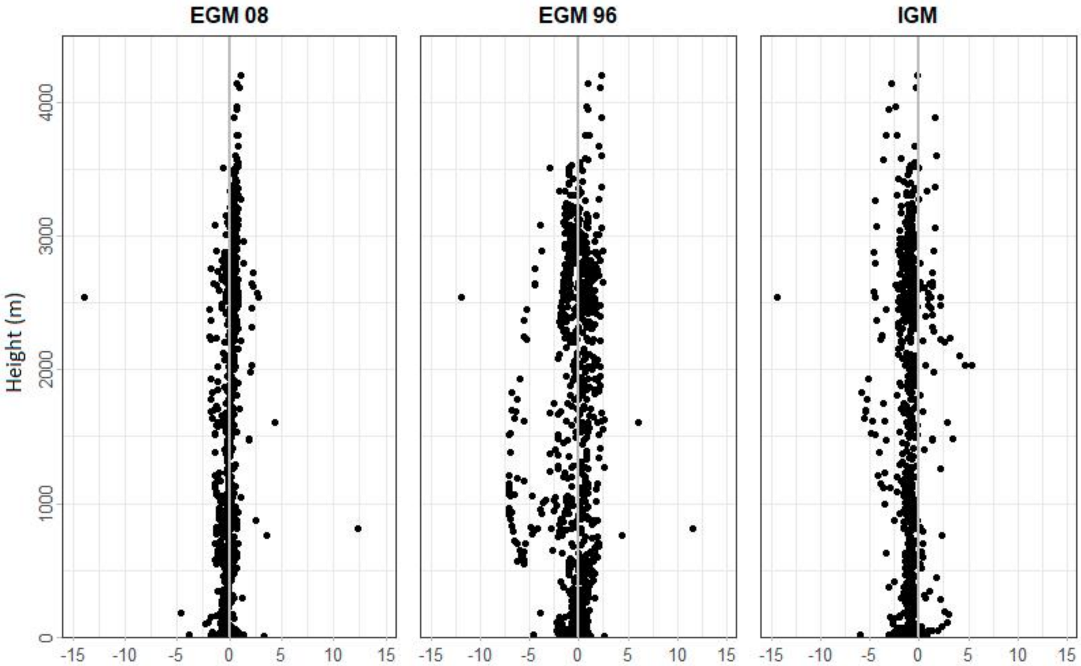

Figure 15. Dispersion of the difference in MGs.

Figure 16 highlights a low number of outliers in the three MGs. The spatial evaluation of the MG EGM 08 shows that there are differences with high values surrounded by differences with low values in the north, while the values in the south show there are differences with low values surrounded by differences with high values. Although the MG EGM 96 has a minimal amount of outliers, they maintain the behavior observed in the MG EGM 08. IGM MG has no pattern in the distribution of outliers.

The RMSE of the MGs is shown in Table 4, where it is verified that the MG EGM 08 has the best accuracy.

Table 4. RMSEs of MGs.

MGs	RMSE (m)
EGM 08	0.82
EGM 96	1.67
IGM	1.43

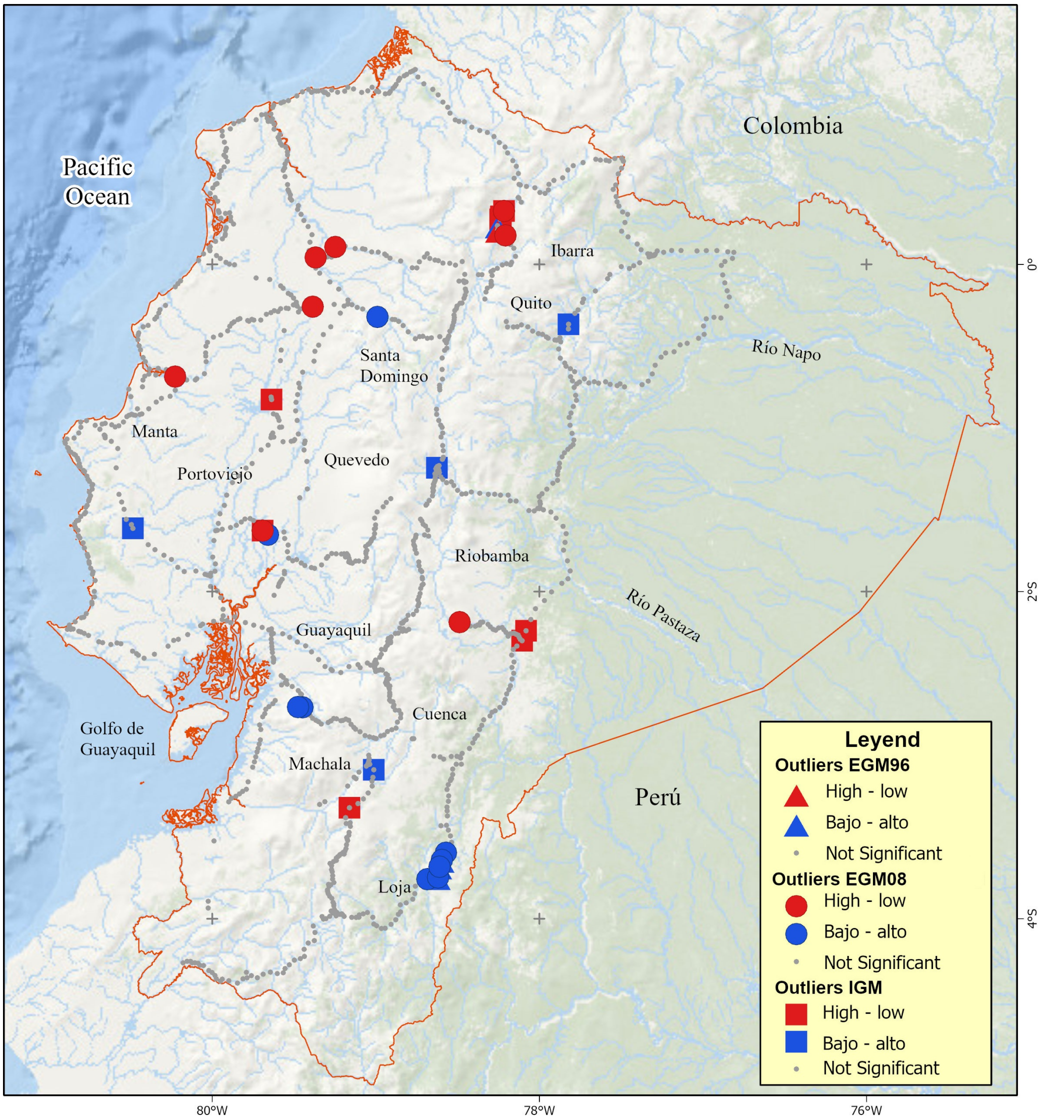

Figure 16. Analysis of atypical values for the differences in MGs.

3.3 Evaluation of ellipsoidal heights of MDTs

We analyzed the distribution of the differences between the ellipsoidal heights captured in the field with respect to the ellipsoidal heights calculated from those of MDTs, except for MDT ALOS PALSAR whose original heights are ellipsoidal heights.

As shown in Figures 17 and 18 and Table 5, there is aError: no se encontró el origen de la referencia similar behavior of box diagrams and distribution of differences in orthometric heights with the MG EGM 96, where symmetry and similarity in size, location and statistical values of MDTs SRTM, ALOS PALSAR and IGM stand out.

Table 5. Ellipsoidal Height Box Diagram Values.

MDTs	Max	Q3	Med	Q1	Min
SRTM 90	8.95	1.02	-1.50	-4.62	-12.98
ASTER	23.51	7.01	1.91	-4.12	-20.80
ALOS 12.5	8.97	1.05	-1.43	-4.26	-11.94
IGM	8.76	0.66	-1.76	-4.85	-13.10

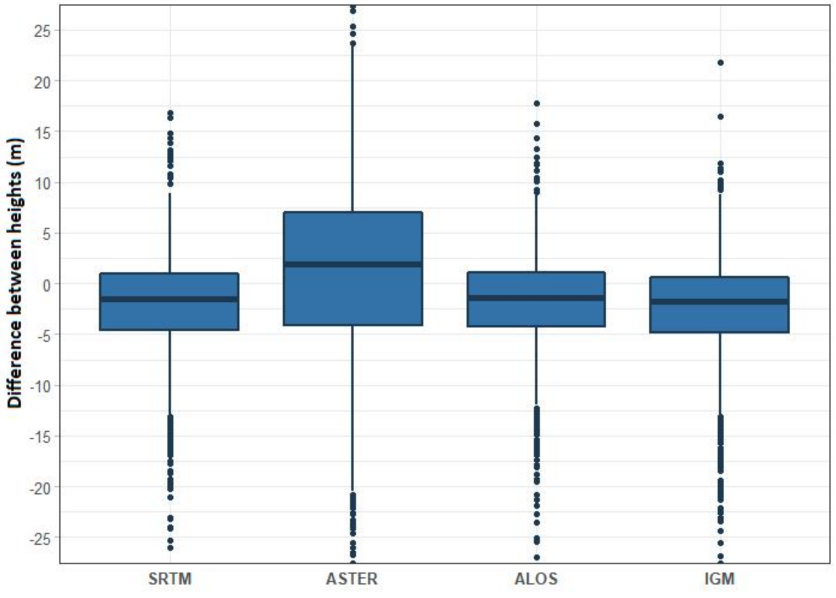

Figure 17. Ellipsoidal Height Difference Boxplot Diagram.

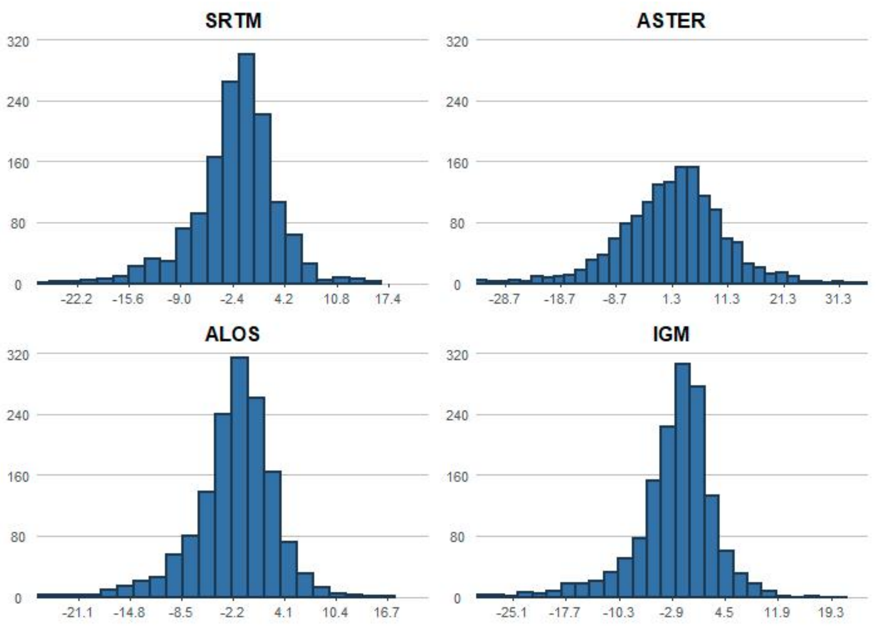

Figure 18. Difference histogram of ellipsoidal heights.

Figure 19 shows that the dispersion of the ellipsoidal heights exhibits the same behavior as the orthometric height differences of Figure 5; however, the differences have a lower dispersion range. In the case of orthometric heights, the differences reach 100 meters, while with the ellipsoidal heights, the differences reach 50 meters.

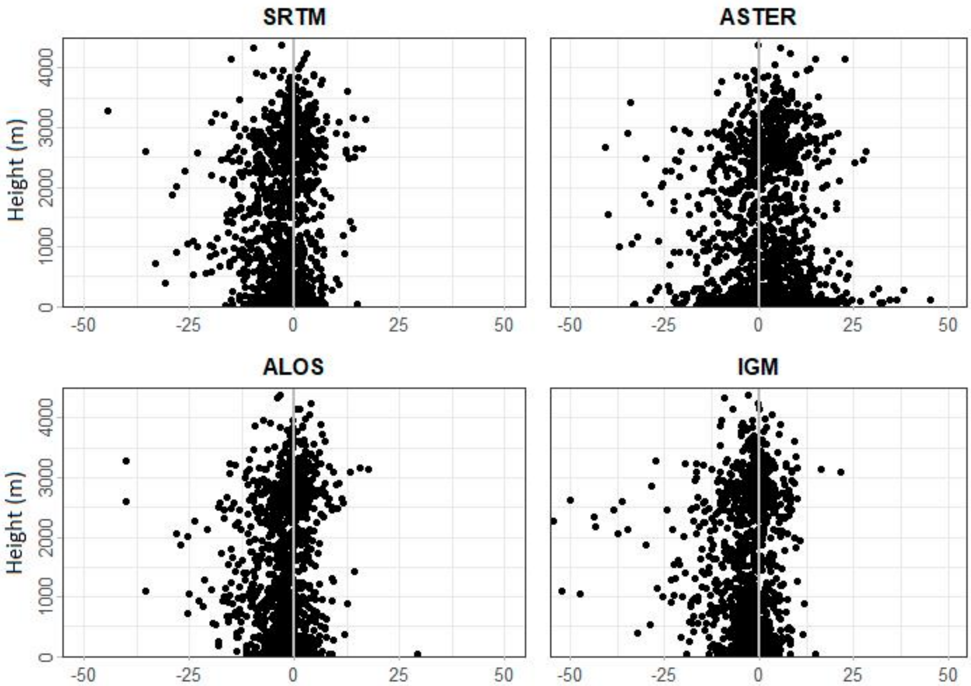

Figure 19. Difference Dispersion of the ellipsoidal heights.

A similar behavior is identified in Figure 20 in the typology and location of outliers in the MDTs SRTM, ALOS PALSAR and IGM, where the largest number of outliers of differences with high values surrounded by differences with low values are present in southern Ecuador, while there is a greater presence of outliers of differences with low values surrounded by differences with high values in central and northern Ecuador. The MDT ASTER GDEM does not present areas where there is a predominance of some type of atypical value. The percentages of outliers of ellipsoidal heights with respect to the original orthometric heights outliers of the MDTs show a slight reduction in the percentage of high-low outliers and a slight increase in the percentage of low-high outliers.

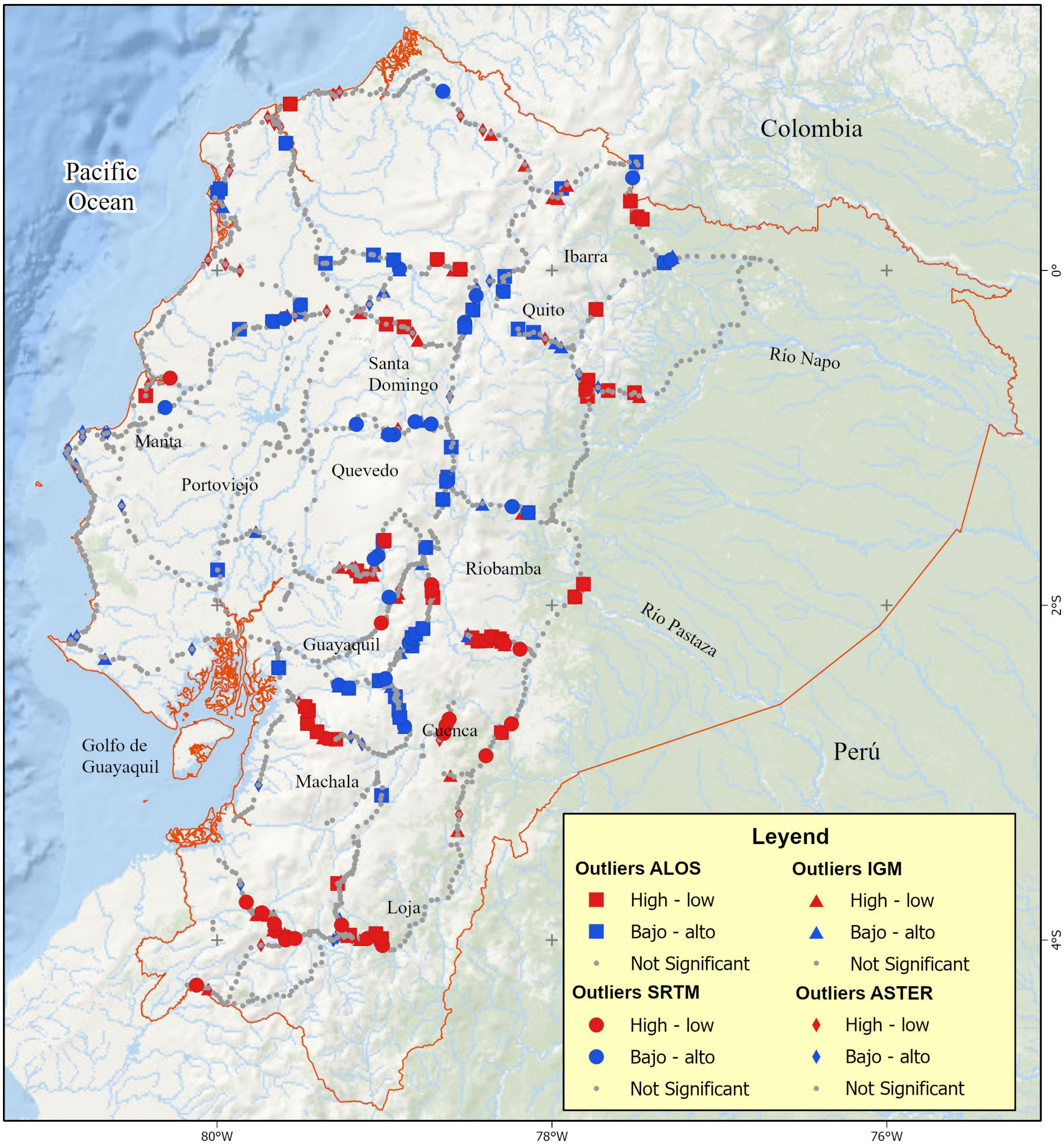

Figure 20. Outliers of differences in ellipsoidal heights.

3.4 Evaluation of orthometric height of the MDTs with MG EGM 08

New orthometric heights for the MDTs were calculated from the replacement of MG EGM 96 by MG EGM 08. In the case of MDT ALOS PALSAR, equation 1 and MG EGM 08 were used to obtain the new orthometric height. The box diagrams, the dispersion of heights regarding the evaluation height and the analysis of outliers did not vary visually with respect to the origin of the reference of the orthometric heights assessment of the MDTs with the MG EGM 96, but there was a slight improvement in the RMSE. Table 6 shows the results of the RMSE analysis of the MDTs with orthometric heights with MGs EGM 96, 08 and ellipsoidal heights.

Table 6. RMSE of the different height systems of the MDTs.

MDTs	Orthometric EGM 96 (m)	Orthometric EGM 08 (m)	Ellipsoidal (m)
SRTM 90	11.20	11.19	10.25
SRTM 30	7.97	7.92	7.06
ASTER	10.76	10.71	10.05
ALOS 30	7.75	7.67	6.87
ALOS 12.5	7.57	7.47	6.74
IGM	8.54	8.50	7.96

4 Discussion

Mancero et al. (2015) used 28 points to evaluate the 90-meter MDT SRTM in the areas of Carchi, Imbabura and Pichincha, located in the northern of Ecuador, determining that the model has an RMSE of 21 (m), and highlighting that the sites with high slope has an influence on vertical precision, data gaps and the sign of errors, while in the sites with low and medium slope, the errors are minor. The RMSE obtained in Mancero et al. (2015) differ from the ones obtained in this research, because the points used in this research were captured in the roads of Ecuador, hence the heights were better adapted to the shape of the terrain with respect to the heights captured in areas of high relief or where vegetation prevails.

Falorni et al. (2005) used 112 points to evaluate the MDT SRTM in the basins of the Washita and Tolt rivers in the United States. Washita characterizes by having a low relief topography except for the steeper hills located in the central part of the north of the basin. Tolt is characterized by a changing topography from the rugged mountains of the easternmost part of the basin, with a high relief and steep slopes to the lowland plains. The difference with the National Geodetic Survey (NGS) was 7.18 RMSE, while with GPS it was 8.94 RMSE. Hirt et al. (2010) determined that the 90-meter MDT SRTM for Australia has a 6-meter RMSE. With all the results presented, it is shown that the RMSE obtained from the MDT SRTM in both resolutions are within the expected range.

Hirt et al. (2010) determined that the MDT ASTER GDEM in Australia has an RMSE of 15 meters. Zhang et al. (2017) evaluated the vertical accuracy of the MDT ASTER GDEM in the northern margin of the Tibetan plateau, for this purpose 89 GPS control points were used and the normal heights were transformed using the MG EGM 96; thus, it was determined that the standard deviation between the MDT ASTER GDEM and the points was 9.3 meters. With all the results presented, it is shown that the RMSE obtained from the MDT ASTER GDEM is within the expected range.

Tierra (2009) used 144 points to evaluate the accuracy of global geopotential models (GGMs) EGM 96 and EGM 08 in continental Ecuador, determining that the MG EGM96 has a standard deviation of 1.35 meters, while the MG EGM08 has a standard deviation of 0.93 meters. The results obtained in Tierra (2009) agree with the results obtained in this research, confirming the improvement between the MG EGM 08 compared to the MG EGM 96, although in both cases geoidal pseudo-undulations were used to evaluate the MGs. Although the evaluation process of the IGM MG is not detailed in Tierra and Acurio (2014), it is difficult to define the reason for discrepancy with the result obtained, but this research maintains the obtained RMSE, since the statistics that support them were presented.

Kotsakis et al. (2010) used 1542 points with GPS data and the level of the Hellenic national triangulation network to evaluate the accuracy of the MG EGM 08, determining a deviation of 0.14 meters. Martínez and Bethencourt (2012) used the high-precision geometric 160-kilometer leveling line existing in Puerto Rico to determine the accuracy of the MGs EGM 96 and EGM 08, determining that the standard deviation of the MG EGM96 is 0.055 meters, while the EGM08 was 0.029 meters. Both studies demonstrate how the steep relief of Ecuador has influenced the loss of precision.

5 Conclusions

The MDT ALOS PALSAR showed the best statistical characteristics, both with orthometric and ellipsoidal heights. MDTs SRTM 30, ALOS PALSAR 30 and 12.5 meters, and IGM can be used in projects that require a vertical accuracy of less than 10 meters or generate maps at a scale of less than 1:50 000, in any height system, either ellipsoidal height or orthometric height.

Spatial resolution is a factor that directly influences the vertical accuracy of MDTs. The 30-meter MDT SRTM improved the RMSE by about 3 meters in all height systems over the 90-meter MDT SRTM, while the 12.5-meter MDT ALOS PALSAR improved the 20-centimeter RMSE over the 30-meter MDT ALOS PALSAR.

The evaluation of the MGs allows to determine that the MG EGM 08 can be used in projects that require orthometric heights with a vertical precision of less than 1.25 meters or a scale less than 1:5 000, since the ellipsoidal heights have a centimeter accuracy greater than 40 centimeters. The MGs EGM 96 and IGM can be used in projects that require an orthometric height with precision lower than 2.5 meters or a working scale of less than 1:10 000, since the ellipsoidal heights have centimeter accuracy greater than 80 centimeters.

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