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Accuracy of contour lines using 3D bands
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This article describes a new methodology for the planimetric control of contour lines. The method is based on the generation of buffers around the contour lines which define a 3D buffer around the maximum slope line. After that we analyze the quantity of points from a more accurate source which is inside this buffer. As a result, we obtain a distribution function of the control points included when we apply several widths to the buffers. We have also determined the angularity and height differences of these points. The method has been applied to several sets of contour line intervals derived from a digital elevation model (DEM) and to the contour lines of one published topographic map using the DEM as the control source. We have also analyzed the representative behaviour of the contour lines, taking into account the contour line interval and the detection of an uncertainty model based on the slope variation. This study demonstrates the viability of the proposed method for obtaining the uncertainty of the contour lines depending on a given level of confidence and the variability of this uncertainty in the map. Finally, we propose a range of contour line intervals based on the scale and slopes.

Keywords: quality; uncertainty; DEM; contour lines

1. Introduction
More and more users of any products demand high levels of quality and, in this sense, users of cartographic products have the same needs. The basic components of quality in geographic data are positional accuracy, thematic accuracy, temporal accuracy, logical consistency and completeness (NCDCDS 1988; ISO 1999, 2002). Among these, positional accuracy is an important factor because it analyzes the spatial component which is the base of any geographic product. The study of this component is fundamental for analyzing the behaviour of cartography. However, the control of heights or Z coordinate of spatial databases (SDB) has traditionally been performed separately from that of the planimetric coordinates (XY). So the determination of this positional accuracy has been based on the use of a sample of well-defined points in the map with known coordinates obtained from a more accurate source. The planimetric position of these points should allow and guarantee their correct identification in both sources (map and control). In this sense, there is a great quantity of standards for the cartographic products based on this analysis of points (NMAS-USGS 1947, EMAS-ASCE 1983, ASPRS 1990, NSSDA-FGDC 1998, SDEM-USGS 1998, ICSM 2009). The majority of these methods are based on the...
independent determination of the vertical error (difference of values, RMSE, etc.) of a sample of points and the contrast of the results with those required by the standard. A more detailed description of some of these standards is developed by Veregin and Giordano (1994).

The current development of acquisition systems and SDB allows the obtaining and management of large quantities of altimetric data. Thus, the use of digital elevation models (DEMs) has been widely extended, providing an additional cartographic product. Even so, the representation of relief in the main cartographic products (national topographic series of maps, land surveys, geological maps, etc.) continues to be performed using contour lines. This wide use is due in part to the fact that contour lines are an easy and very visual way of representing the three-dimensional behaviour of the terrain in the bi-dimensional format of the map. By definition, contour lines represent a chain of infinite points located at a determined height. This definition supposes that each contour line is determined by the intersection of a parallel surface (generally a plane) to one of reference (origin of heights) with the terrain. This parallelism helps users (even those who are not experts) to acquire the idea of relief. The system of contour lines has been in use for a long time, so the main body of altimetric information of historical spatial data is only available in this way. In recent years, the main evolution has been achieved in acquisition systems and analysis and visualization technologies (DEM, LiDAR, etc.), which have allowed the development of other representation systems (e.g. 3D models), although the traditional contour lines are still widely used. The main difference between current maps of contour lines with respect to previous ones is the acquisition source. Traditionally these contour lines were obtained by photogrammetric restitution, while nowadays they are obtained by the interpolation of DEMs generated from photogrammetric matching or LiDAR systems. The development of these technologies has led to a great quantity of studies which analyze the positional altimetric quality of these products (Li 1994, Walker and Willgoose 2006, Aguilar and Mills 2008, Höhle and Höhle 2009, Aguilar et al. 2010) by means of different sequences of parameters (Karel and Kraus 2006). This quality control of DEM is being developed at institutional level in the collaborative environment of international projects like EuroSDR. The official publication 60 of EuroSDR (Höhle and Potuckova 2011) is completely focused on methodologies for testing and improvement of DEMs. In this document, some researchers apply different methodologies, automatic and semiautomatic, for controlling three DEMs obtained using different methodologies (photogrammetry, laser scanning and contour lines) analyzing the results both for quality and degree of automation. However, none of these studies analyzes the quality of the representations obtained from these products both in planimetry and height (in this case, contour lines). For example, the usual control carried out on contour lines has been performed using a set of points from a more accurate source by analyzing the percentage of them which are inside (planimetrically) the two contour lines corresponding to the height, but without taking into account the planimetric positional accuracy of these contour lines (NMAS-USGS 1947). However, there are two potential sources of uncertainty when analyzing the accuracy of contour lines. The first is the positional error, and the second is the difference between model terrain and real terrain not represented by contour lines.

Another important issue when analyzing the positional accuracy of heights is the study of the effects on the vertical component derived from the slope of the terrain, taking the vertical mean error using Koppe’s formula. This expression relates the vertical and horizontal mean error to the tangent of the slope (by a regression) and can be used to analyze the accuracy of contour lines between two maps (Gustafson and Loon 1982, Imhof 2007). Koppe’s formula is shown in Equation (1), where $A$ and $B$ are two empirical constants determined for a particular map and $\alpha$ is the slope:
Taking this expression into account, some institutions have established tolerances in function of the slope and the map scale (Imhof 2007). However, we consider that contour lines are linear elements in the maps with a specific characteristic which is the height represented. In this sense, the analysis of the accuracy of these elements could be obtained in the same way as other line features in a map (e.g. roadways), but taking into account their representation of height value. From a planimetric point of view, the main studies which analyze the positional uncertainty of linear elements are based on the existence of an uncertainty band (epsilon band) around the line, described by Perkal (1956) and expanded by Blakemore (1983). In this model, the most probable position of the line is situated inside a defined displacement (epsilon) around the measured position (Zhang and Goodchild 2002). This band is initially defined for a simple segment by two lines parallel to the more probable line and tangents to the circular error in the final points of the segment. Subsequently, the concept of this band has been expanded by other models. For example, Caspary and Scheuring (1993) describe an error band with a minimum uncertainty in the middle of the segment, and Cheung and Shi (2004) describe an integrated error band based on bi-dimensional distributions (ellipses) developed from a sample of points which are inside the line.

The determination of the uncertainty band for any line has been widely analyzed in the literature and several methods have been described (Skidmore and Turner 1992, Abbas et al. 1995, Goodchild and Hunter 1997, Tveite and Langaa 1999, Mozas and Ariza 2010, 2011). In general, all the methods which have been proposed are based on obtaining the positional accuracy of lines by two methods: point-based and line-based. The first consists of the measure of Euclidean distances from the vertexes of one line to the other line (control and to be controlled), and the second is based on the determination of the uncertainty band around the line to be controlled. If we take into account the particular case of the contour lines, this error band is influenced by the slope and the mean error of the points which determine the contour line (Yoeli 1984). This concept is used and expanded by Gökgöz (2005) in analyzing the generalization processes of contour lines using Koppe’s formula in order to determine the error of the points of the contour lines based on the local slope. However, this technique requires a previous estimation of the planimetric error of the points of the contour line for a determined scale. In this way, the constant values of Koppe’s formula are estimated.

Thus in order to avoid the inconvenience of estimating the planimetric error of the contour line, in this study we propose the determination of an empirical value of the positional uncertainty of the contour lines using a more accurate altimetric source for a given level of confidence. We propose the use of the model of determination of uncertainty of linear elements based on a simple buffer (described by Goodchild and Hunter 1997). This method consists of the generation of one buffer around the control line (from a more accurate source Q) and the determination of the percentage of length of the line to be controlled (X) which is inside it (Figure 1). If the buffer width is increased, we can obtain a distribution function of probability of the uncertainty of the line. A preliminary study for adapting this method to contour lines is described by Ureña et al. (2011). The adaptation proposed by Ureña et al. (2011) substitutes (i) the buffer around the control line with a buffer around the controlled line (contour line) and (ii) the control line with a set of height points obtained from a more accurate source (e.g. GPS survey and DEM).

To summarize, in this study we have extended the methodology described in Ureña et al. (2011), which allows us to determine the positional quality of a set of contour lines from two points of view: planimetric, adapting a method for controlling the positional
accuracy of lines, and altimetric, because the height of the contour line will be the basis for determining this planimetric uncertainty. Moreover, the methodology proposed in this article extends the previous one by analyzing the sensibility of angles between vectors of local slopes, differences of the interval between contour lines and the individual analysis of points. The proposed method is applied to a real database of contour lines using a set of points obtained from an official DEM to control the lines. This method constitutes a mixture of those applied to linear elements because it uses point-based and line-based techniques. Finally, we analyze the representation of individual points and propose a range of contour intervals for different sets of scales and slopes.

2. Methodology

In order to adapt the method initially proposed by Goodchild and Hunter (1997), we generate two buffers around two contiguous contour lines planimetrically. As a result, the buffer is also applied to the maximum slope lines which exist between both contour lines. This creates a 3D buffer around the maximum slope lines. Afterwards we analyzed the quantity of points from a more accurate source which is inside the buffer obtained around the maximum slope line and which passes by the point on the profile (Figure 2a). After that, we increase the buffer width and then quantify the number of points which are included in the new buffers around each maximum slope line. In this way, we obtain a distribution of points which is inside the buffer around the maximum slope line.
probabilities based on the percentage of points which are included in the buffers in function of their width. This distribution indicates the global planimetric uncertainty of the contour lines analyzed depending on the level of confidence.

In Figure 2a, point \( p \) is included in the buffer generated around the line of the slope in the profile if the distance \( x \) is lower than the width of the buffer \( b \); however, point \( p' \) is outside this distance due to differences in height and horizontal position. The distance of the height corresponding to the point based on the slope line with respect to the upper contour line \( (d) \) is obtained using the triangle similarity where \( D, h \) and \( H \) are known. The best way of obtaining the maximum slope line between both contour lines, which passes by the point, is based on the perpendicular directions to those contour lines. Actually this line is composed of two lines from the control point to the closest point of each contour line in the majority of cases. In this way, the distance will be calculated using the simple relation described in Equation (2). So point \( p \) is inside the buffer while point \( p' \) is outside that region and it will not be quantified for the width applied:

\[
d = \frac{D \cdot h}{H}
\]  

(2)

The set of control points used for the proposed methodology must come from a more accurate source. So we propose the use of a more accurate DEM or a database composed of a great quantity of points (obtained from GPS, LiDAR, etc.) with more accuracy as well. In this article, we suppose that the control points come from a height grid because nowadays this is a common product in institutions all around the world. We also recommend the use of a great quantity of control points (large sample size) in order to avoid distortions caused by local variations of the terrain that could affect control points but which are not represented at contour line intervals. In some cases, a previous smoothing of the set of points is recommendable (e.g. when using LiDAR with noisy data).

Following these premises, the process for applying this method attempts to determine the minimum distance to the contour lines from each control point considered. A summary of the main stages is described next:

(1) Selection of the contour lines to be controlled.
(2) Selection of the sample of control points. We must select a wide sample of control points from a more accurate source. The initial point database must pass a filtering process in order to prepare the control database for the application of this methodology. This process will reject
   • Singular points. This method cannot use singular points like local minimum/maximum heights (included only inside one closed contour line).
   • Points with low slope. We use a filter based on a maximum distance (e.g. 500 metres) with respect to the two closest contour lines in order to avoid points located in low-slope areas. Thus, the minimum useable slope is about 0.02%.
   • Points not placed between the correct contour lines. This problem can be originated by datum problems, temporal discrepancies or any other circumstances between contour line database and the control DEM.
   • Points situated on the border of the map (or sheet) and thus having only one enclosed contour line.
(3) Selection of the two contour lines with the minimum Euclidean distance to the considered point taking into account the heights of these contour lines and of the point.
(4) Filtering the set of control points selecting the points with vectors to the contour lines in similar directions. For this purpose, we limit to 10° (planimetrically) the
maximum deviation between the directions of the slope lines obtained from the point to both contour lines. This value has been determined analytically by a comparative analysis using several filtering values (see the results section). Figure 2b describes this process where point \( q' \) is rejected because the angle between the directions of vectors is higher than the limit of 10°.

(5) Determining the statistical parameters for the selected points and their corresponding contour lines (e.g., planimetric distances from the point to the two contour lines).

(6) Repeat the whole process for a set of widths. We must generate the buffers with several widths, calculate the distances to the contour lines, the slope, etc., and quantify the percentage of valid points which are inside the buffers. So we can obtain the statistical distribution function of inclusion of points related to the buffer width and estimate the positional uncertainty of the contour lines.

3. Application

An application of the methodology to a database was developed using an area of 7400 × 4700 metres corresponding to a sheet from the Topographic Map of Andalusia at scale 1:10000. The DEM (DEM10m) used for controlling had a spatial resolution of 10 metres and was obtained from the DEM as a derived product of Orthophoto by the Instituto Cartográfico de Andalucía. The height accuracy of this DEM10m is approximately 1.0 metre, obtained from an analysis based on control points with a horizontal accuracy better than 0.3 metres in a regular sampling using the EuroSDR recommendation (Karel and Kraus 2006). The proposed method was applied twice. The first one (control case) was used as a control process of the methodology by applying it to DEM10m (Figure 3a) and the contour lines derived from it (CL5m, CL10m, CL15m and CL20m) (Figure 3b–e). The second application (real case) was performed using the same DEM10m and a contour line set obtained at another scale (called CL25k) (Figure 3f). The selected area for these applications is derived from a previous study where we took into account the selection of one zone with valleys and medium-sized mountains with several slope values and a regular distribution of heights. The proposed methodology was implemented using a computer application developed by us in Java™ for this purpose. The buffer widths used in this study were from 1 to 20 metres increased by 1 metre and from 25 to 50 metres increased by 5 metres.

Finally, in order to contrast the methodology described in this study, we applied an experiment using the methodology described in the National Standard for Spatial Data Accuracy (FGDC 1998). Following this standard, we selected 100 points randomly from the set used in our application. After that, we interpolated height values from the closest contour lines. Then we determined the error of height for each point and projected planimetrically using the local slope, thus determining the root mean squared error (RMSE) of height and planimetry and subsequently estimating a 95% level of confidence applying the factors proposed by Greenwalt and Schultz (1968).

3.1. Control case

First, we used a control case in order to check the methodology. This test case is composed of four sets of contour lines with different contour intervals of 5, 10, 15 and 20 metres obtained from the same DEM used for controlling (these sets of contour lines are called CL5m, CL10m, CL15m and CL20m, respectively) (Figure 3b–e). The use of this case
is justified in order to test the proposed methodology using a set of contour lines which have no datum problems or displacements with respect to the control data. These four sets of contour lines were interpolated using the algorithm developed in the software ArcGIS Desktop 9.2 by ESRI (from Arctoolbox 3D analyst module/Raster Surface/Contour).

The definitive sets of control points are composed of 74,236, 45,535, 34,165 and 26,807 points for the control cases (DEM10m vs. CL5m, DEM10m vs. CL10m, DEM10m vs. CL15m and DEM10m vs. CL20m, respectively). All these sets of points are obtained after imposing a minimum angle between the directions of the vectors from the control point to the contour lines of 10°.

3.2. Real case

Once we checked the method by using the control data, we also applied it to real data. More concretely we used a set of contour lines (Figure 3f) (called CL25k) from the same geographic area, obtained from the National Topographic Map at scale 1:25000 produced by the Instituto Geográfico Nacional (Spain). The contour interval is 10 metres. We note
that the DEM10m and CL25k databases were related to the same reference system and projection (ETRS89-UTM30 and orthometric heights). The definitive set of control points is composed of more than 36,000 points for the real case (DEM10m vs. CL25k).

4. Results and discussion

4.1. Control case

The results obtained with the application of the proposed methodology to the four sets of data (CL5m, CL10m, CL15m and CL20m) are shown in Figure 4a. Logically the representation of the terrain is improved with the reduction of the contour interval and the behaviour of the curves in the distribution function is consequently better. The results have shown that the DEM10m spatial resolution is adequate for all the contour intervals because all cases have more than 60% of line lengths shorter than the cell diagonal distance.

One important issue of the methodology is the determination of the maximum angle between the directions of the vectors representing the minimum Euclidean distance between the control point and both contour lines. To choose the most adequate value, we have used several limiting values of angles of 30°, 20°, 10° and 1° between these vectors. This study is applied to the CL10m data set exclusively. In these circumstances, we obtained sets of 107,749, 80,720, 45,317 and 4811 points, respectively. Logically the reduction in the number of points is related to the limit of the angle imposed. We also analyzed a general case without filtering where all angles were included. After applying the method, we obtained the results shown in Figure 4b. In this case, we can see that the higher limits obtain better results of inclusion. Keeping this result in mind we selected the 10° value in order to balance the reduction in the number of points to be used and the precision of the results. Therefore, this is the limit applied in this study and the one recommended for the application of this methodology.

Finally, the results of the application of the proposed methodology to the CL10m data set, which has the same contour interval as the real case (CL25k), are shown in Figure 5a. We can see the increase of the inclusion percentage with the buffer width. So the 90% value is achieved with a width of 16 metres and the 50% with 3 metres. If we cross-analyze the inclusion percentage and the local slope of the control points (classified into intervals), we obtain the results also shown in Figure 5a. This local slope is obtained using the Euclidean distances between the control point and the contour lines. In this graph, we can see that the best results of inclusion are obtained with the increase of the slope.

Figure 4. (a) Results of CL5m, CL10m, CL15m and CL20m; (b) results of CL10m data based on the filter value of the angle between vectors. X-axis: buffer width; Y-axis: percentage of inclusion.
Figure 5. (a) Results of DEM10 versus CL10m by slope intervals; (b) results of DEM10 versus CL25k by slope intervals. X-axis: buffer width; Y-axis: percentage of inclusion.

With regards to the application of the NSSDA methodology, the results show values of 1.72 metres of accuracy in the Z component and 20.58 metres of accuracy in XY (RMSE at 95%).

4.2. Real case
The results obtained when applying the proposed methodology to the real set of contour lines are shown in Figure 5b. In this case, we can see a graph with a similar distribution function to the control case but with a reduction in the inclusion. Thus, a 50% inclusion is achieved with 9 metres and 90% with 35 metres. These values are lower than those obtained for the CL10m case but very similar to the CL15m case.

The analysis of slopes has also shown graphs with curves very similar to those obtained in the control case where the inclusion ratios grow with the slope (Figure 5b).

Finally, the results obtained by applying the NSSDA show an accuracy of 3.69 in Z and 39.02 metres in XY (RMSE at 95%).

4.3. Discussion
The uncertainty detected in the control case is due to the spatial resolution of control data (10 metres in planimetry), the process of the contour lines generation (smoothing, generalization, use of splines, polylines, etc.) and the selected contour interval. Logically the results obtained when we classified the study by slopes show that the zones with smooth slopes have higher planimetric uncertainties than the ones with higher slopes. This is consistent with the concept of mean vertical error described by Koppe’s formula (Gustafson and Loon 1982, Imhof 2007). In this sense, we propose that the values of uncertainty obtained for different intervals of slope can be represented using contour lines with variable widths related to these uncertainties (Imhof 2007). We also propose the representation of intermediate contour lines locally in cases with lower slope values (Imhof 2007) in order to guarantee a stated level of planimetric accuracy. This supposes a reduction of the contour interval for these cases or zones. We also propose the gradual representation by slope or the densification of spot heights to minimize the planimetric effects of this uncertainty.

The results of the set of contour lines from the map 1:25000 show higher uncertainties for high percentages of inclusion overall (35 metres for 90% of probability – Circular Map Accuracy Standard (CMAS) – and 9 metres for 50%). These values are
derived from several factors which contribute to positional uncertainty such as (i) the positional discrepancies between planimetric position and height of the contour lines with respect to the set of control points; (ii) the uncertainty of the representation system, the acquisition process (also presented for the CL10m data) and (iii) the temporal and datum discrepancies between the DEM data set and the contour line data set. Even though these differences exist, the comparison of the results shows similar trends, and we consider that this methodology is useful for controlling contour lines.

The comparison of the results obtained with the methodology described in this study and those given by the application of the NSSDA shows similar values with a 95% of inclusion (level of confidence for the determination of the positional accuracy by NSSDA) for both control and real cases. However, the results obtained using our methodology not only define a value of inclusion but a complete density function dependent on the population (set of points used in the methodology). Furthermore, the complete control is obtained automatically for several ranges of slopes and levels of confidence.

If we compare the results of both sets of data, the CL10m case shows a higher accuracy (more percentage of inclusion at lower distances) with respect to set CL25k. This is a logical result because the first is derived from the control DEM while the second comes from an independent source. The planimetric uncertainty obtained through the proposed methodology shows some differences between the distribution functions of both sets of contour lines analyzed. Logically the results of the control case (CL10m) show a graph with higher percentages of inclusion than the real case (CL25k). So CL10m shows only the uncertainty in the representation system (mainly by contour line intervals) while CL25k shows all the previously described sources of uncertainty.

On the other hand, we have represented the individual differences between the set of control points and the interpolated control points for both DEM10m versus CL10m (Figure 6a) and DEM10m versus CL25k (Figure 6b).

![Figure 6](image-url)
Table 1. Recommendation of maximum and minimum contour line intervals (in metres) based on slope and scale.

<table>
<thead>
<tr>
<th>Slope/scale (%)</th>
<th>0.25 mm</th>
<th>0.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1:10000</td>
<td>1:25000</td>
</tr>
<tr>
<td>5</td>
<td>0.5–1</td>
<td>1–5</td>
</tr>
<tr>
<td>10</td>
<td>0.5–5</td>
<td>1–10</td>
</tr>
</tbody>
</table>

The results for the first case (Figure 6a) show that DEM10m is sufficiently accurately represented except in some zones where the differences between interpolation and DEM10m data are near to 8 metres. However, the majority of control points are below 2 metres. Regarding the second case (Figure 6b), the differences are higher with more control points near to 8 metres (red zones in Figure 6b).

More interesting is the planimetric position of these differences, as is shown in Figure 6a, the control points that are less accurate in height the farther they are from the contour line. However, in Figure 6b, these differences are close to the contour lines, meaning that these contour lines represent the DEM10m worse, which is consistent with the different origin of both sets of contour lines.

Finally, we propose a range of contour line intervals based on slope and scale. These values are shown in Table 1. The recommendation is made in upper and lower interval limits. The lower limit is obtained from the minimum Euclidean distance between two adjacent contour lines and the slope between them. The minimum distances applied are 0.25 mm (used by ASPRS 1990) and 0.5 mm at map scale. The upper limit is obtained by applying the previous distances to the interpolated values obtained from control case, using the 90th percentile of distribution functions of CL5m, CL10m, CL15m and CL20m (according to CMAS).

5. Conclusions

The study described in this article has demonstrated the viability of the proposed methodology for controlling the positional quality of contour lines based on linear elements techniques. The method allows us to determine the planimetric uncertainty of the contour lines with a given level of confidence using a set of points of known height obtained from a more accurate source.

This study has also demonstrated that the selection of the contour interval is a fundamental factor to take into account in order to properly represent the heights in a map. The reduction of the planimetric uncertainty of the contour lines is directly related to the reduction of the contour interval. Furthermore, this factor is more important in cases with smooth slopes. For this reason, we have recommended a range of contour line intervals based on scale and slope determined from the accuracy of contour lines checked in the application.

We analyzed several contour line intervals obtained from the same DEM in order to determine the representativeness of each case. We also analyzed the curvature of terrain...
using two approaches: (i) determining some deviation values (angles) between maximum slope line and the two Euclidean distances from the point to the adjacent contour lines and (ii) determining height differences between the control points and the interpolated points using the contour lines. The first approach has revealed that angular differences greater than $10^\circ$ indicate that this control point is not well represented by the contour lines. The second approach shows that the spatial distribution of high differences near to contour lines reveals that the contour lines are not appropriate for representing these zones.

The results have been contrasted with a point-based quality control methodology (NSSSDA) showing similar values of planimetric accuracy for the 95% level of confidence. Thus, the methodology proposed in this article agrees with standards generally applied to this positional quality control. Furthermore, our methodology improves the other by analyzing continuous elements, showing the inclusion for all levels of confidence and ranges of slopes.

Finally, this methodology allows the determination of the uncertainty of the contour lines (in a global way) and the accuracy of each zone of the map (using angularity and height differences). Moreover, with the accuracy determination we recommend a range of contour line intervals based on the scale and slopes on a map.

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