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ISOMDE: A NEW APPROACH TO THE GENERATION OF DIGITAL TERRAIN MODELS.

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ABSTRACT

Many spatial applications require the use of Digital Terrain Models (DTM) of variables such as elevation, climate, etc. Although there often exist such models in the form of a raster DTM, in some cases the only terrain model that is available is in the form of less adequate models such as isolines (contour lines, isotherms, etc.). When such is the case it is not a trivial process to obtain a DTM since isolines present some special geostatistical properties. Additionally, other complementary data sources of height and morphology information should not be discarded in the process of DTM generation, despite the fact that their data size makes them seem of less importance.

This work presents a methodology for obtaining raster DTMs which makes use of the different datasets available: isolines, 2D and 3D breaklines, polygonal zones with constant value (e.g. lakes), point data, NoData zones, 3D objects (e.g., roads), etc. The implemented methodology is not a single algorithm but a set of heuristically selected procedures. As opposed to other methodologies, in order to generate the DTM this proposal performs a totally vectorial geometrical analysis, uses different weighed procedures and function types (constant values, linear functions, cubic functions, etc.) depending on the vicinity of each point in the territory and topological considerations are also used when necessary.

This methodology has been continuously refined and applied to several scenarios (la Garrotxa, Andorra, Iberian Peninsula, etc.) with a high degree of success (for instance, in la Garrotxa county, an independent test of 73 343 elevation points detected 1.04 m error in 68 % of points for a 2.5 m resolution of the DTM).

***Key Words**: DTM, DEM, spatial interpolation.*

INTRODUCTION

Knowledge of the spatial distribution of variables with continuous variation across the territory, such as altitude or precipitation, is of paramount importance in many basic and applied studies. Although, thanks to remote sensing techniques, good models of these distributions are increasingly available, in many areas the only (or best) source of information is still frequently in the form of lines of constant value (isolines). Even so, knowledge of the value at any given point, and interpolation from isolines, is not a trivial process, since the data present certain spatial geostatistical characteristics: high redundancy along the isolines themselves (many objects with the same value), which contrasts with large areas without data (in "flat" areas, with very few isolines). Furthermore, the enormous volume of data available makes isolines a significant and unpredictable source of data, and several methods for their interpolation have been proposed.

Traditionally, most of the altimetric information (specifically, altitude) incorporated into Geographic Information Systems (GIS) originates from the contour lines of topographic databases. Additionally, there are other sources of altimetric information: elevations, geodetic vertices, ridge and valley lines, 3D roads, etc., which should be used to adjust the model in specific areas (nearly flat extensions, local maxima and minima), enrich certain profiles, verify the quality and consistency of the model, etc. However, if the curves are reliable, accurate, and detailed, they must play a fundamental role in the generation of the corresponding Digital Elevation Model (DEM) and not simply delegate them to the role of mass supplying points with altimetric information. Furthermore, it is important that the interpolation procedure take into account not only geometric elements but also the topological characteristics of the objects involved, which are often overlooked.

DEMs whose origin is directly (or can be translated in an elementary way into) a raster model are currently beginning to proliferate. However, for the time being, their resolution is still far from that achieved by classical models; for example, the Shuttle Radar Topography project. Mission *SRTM* (2000) presents a resolution of 90 m, while a 1:5000 topographic survey can easily lead to resolutions of 5 m or even lower (2.5 m); in other cases, the data are not accessible to the “general GIS public” due to their high costs (LIDAR) compared to the costs required to implement the methodology presented in this work.

Nor has the digital matrix (raster) model been replaced as the best fit for the DEM-derived uses carried out within the various GIS applications in the diverse fields of study. Indeed, the raster model remains typically the most functional for any analysis and modeling where there is a spatial dependence on the topographic altitude variable.

Given the relevance of traditional sources of altimetric information and the usefulness and versatility of the raster model as a representation of relief, it seems entirely appropriate to review and update the procedures for generating DEMs from isolines, making better use of current computer capabilities, along with the experience and evolution of previous models.

This paper presents a method for generating raster DEMs, which uses altimetric information of different nature, based fundamentally on isolines, but which also considers multiple morphological, geometric and topological aspects during the different phases of data incorporation, interpolation and verification of the coherence and quality of the model.

Although the method proposed in this paper is specialized in generating a DEM from altimetric data, it can be used without any restrictions for any other variable for which constant value lines are available, such as, for example, digital temperature models from isotherms.

The following section will first analyze the different possible information sources: their nature, format, and functionality; second, explain the interpolation procedure; third, detail some of the complementary mechanisms used to test the consistency of information sources, calculate an RMS to determine an objective value for model quality, and provide some complementary methods for achieving greater continuity between models generated from cartographic series sheets and for reviewing consistency across the entire set of cartographic databases used. Finally, the results of two practical applications generated with these methodologies will be summarized: the Andorran DEM and the Garrotxa region DEM.

SOURCES OF ALTIMETRIC INFORMATION

As anticipated in the introduction, the primary source of altimetric information (or the variable to be interpolated) must be contour lines (or isolines). In the specific implementation, the contour lines to be used must be merged into a single file, which must be a structured MiraMon *Pons vector file.* (2000), in ARC binary format. This file can be 3D (each vertex has XYZ coordinates, usually imported from a CAD format), or it can be 2D, in which case a field must exist in the database with the corresponding altitude for each graphic entity.

The equidistance parameter, which defines the difference in altitude between two consecutive curves, will first limit the altimetric accuracy of a valid generated model and will also be used as the value that limits the areas where non-linear interpolations are applied.

Although not essential, to obtain a high-quality model, it is important that the curves are topologically correct, have no intersections between them, discontinuities are eliminated, and all the curves that mark the defined equidistance are available (there are no gaps in the different altimetric levels).

Ridge and/or valley lines can be used as additional sources of information. These will be used to adjust local minima and maxima, or if they correspond to 3D objects, to add altimetric information to the generated profiles (how to do this will be detailed in the interpolation section). Other 3D linear entities, such as roads, can also be added for the same purpose: to enrich the profiles, without requiring a minimum or maximum. It is important to verify that this information is consistent with the contour lines, for example, that the coordinate of each vertex has a value between the nearest neighboring contour lines. In the specific implementation, all this information must be in separate vector layers.

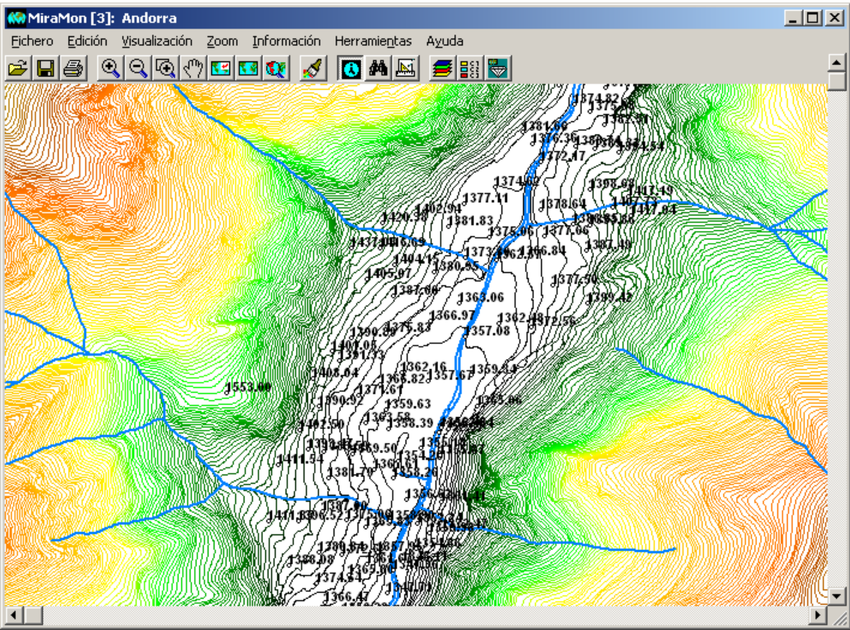
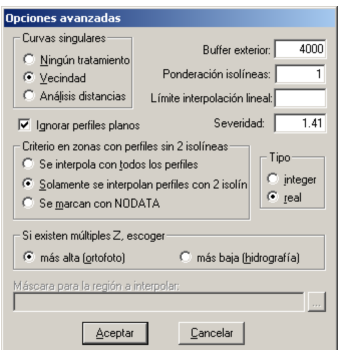


Figure 1 Sources of altimetric information from a 1:5000 topographic map of **Andorra**

Another type of information that can be incorporated are areas of constant altitude (for ex-



ample lakes) as structured vector files of polygons (in MiraMon's POL binary format in the implementation carried out). In this case, it will not be relevant information for interpolation, since it simply smooths the terrain in these predefined areas.

As an additional source, the incorporation of local maximum and minimum bounds into the process is being developed to more accurately adjust these unique areas. To date, in the applications already implemented, bounds from the entire study area have been used to assess the error of the adjusted model (see the model validation section).

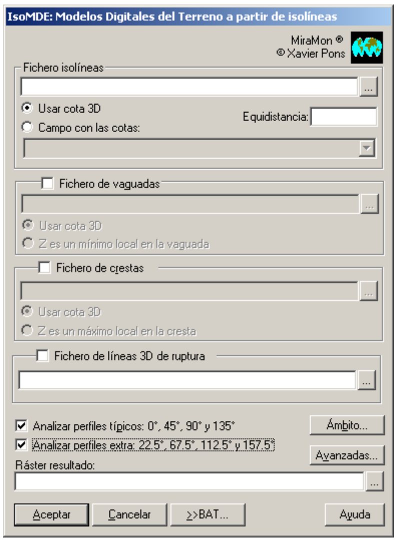


Figure 2. Dialog boxes for configuring the main control parameters of the interpolation procedure and for choosing the information sources

INTERPOLATION PROCESS

The interpolation process does not consist of a single algorithm, but rather consists of a set of procedures and rules heuristically selected from among several of those proposed in the specialized bibliography, *Douglas* (1983), *Douglas* (2000) *Douglas* (1986), *Laurini and Thompson* (1992), *Maune* (2001), *Felicísimo* (1994) and *Taud et al.* (1994). The basic procedure is the drawing of profiles between the contour lines and also considering the intersections with other 3D entities, such as roads, ridges and gullies. Considering the special arrangement of the data in the contour lines, with many data of equal value very close but aligned and large areas without any data between them, this method is usually better than the application of interpolants between points.

On each cell of the resulting raster model, 8 profiles are drawn (every 22.5º) that explore all the possible information around it in a similar way to how other previously proposed algorithms operate, essentially based on *Douglas 's algorithm.* (1983) and *Douglas* (2000) (a reduced version of 4 profiles has also been developed for more modest purposes, where execution time is prioritized). The acquisition of information in this cell environment is carried out in a purely vectorial manner since the methods that previously rasterize end up performing the calculations from original positions displaced towards the cell centers of the raster that is intended to be obtained and, in addition, generate artifacts when exploring following the movement of the bishop that does not detect certain intersections. It is in the tracing of these profiles where the special conditions of topology of the contour lines, the imposition of maximum or minimum conditions of the crest or trough lines and some additional parameters of greater control (advanced options) are used.

These profiles are drawn using different types of functions (constant values, linear functions, cubic functions, etc.) depending on the environment of each point in the territory. This avoids the problems of excessive simplicity resulting from applying only linear functions (peaks and valleys would remain as horizontal planes), but it also avoids the artifacts and slow calculations that can arise if cubic functions or *splines are applied* constantly.

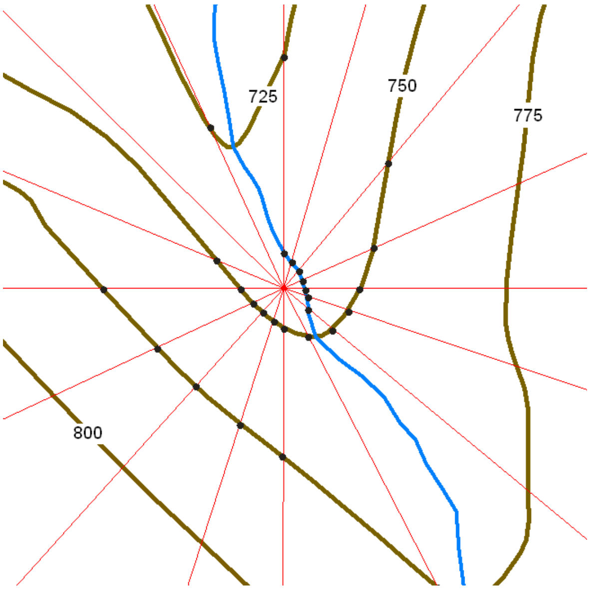


Figure 3. From the problem point corresponding to the cell center, the profiles that intersect with the contour lines and a valley line are drawn.

Using information from all profiles, the final value of the corresponding cell is determined by considering different weights weighted by distance. This weighting of the different profiles is modulated by an inverse function of the distance, with behavior controlled by the exponent. This ensures that the interpolation is accurate when a vertex coincides with the cell center. The recommended value for the exponent is 1.0, as it has been proven to generate a satisfactory DEM and a derived slope model; however, a value of 1.2 gives better results if we are only interested in the elevations. The involvement of all profiles in the value of each cell allows for a much less complex result than that obtained with simple choice methods (profile with the steepest slope) and avoids having to smooth the final DEM by applying average filters, which end up impoverishing the quality of the model.

If the altimetric information is adequate, the general procedure explained so far satisfactorily resolves the vast majority of situations and generates a highly valid DEM, mostly smooth, but at the same time reproducing abrupt morphologies. If artifacts are observed in the result, these can be minimized or even eliminated by appropriately adjusting some of the specific parameters or ***advanced options*** detailed below:

- **Treatment of singular curves** : For isolated curves in the middle of a large plain, which can give star shapes in the interpolation, there are different levels of treatment: no special treatment, resampling in a close neighborhood, additional resampling after analyzing the distances to more distant curves.

- **External isolines criterion** : **When** there are cells where certain profiles intersect with a single profile (typically cells beyond the outermost isoline), you can choose to transfer the altitude of this single profile, ignore this profile using the rest of the profiles or mark the cell as a NODATA value considering it non- interpolable.
- **Limit of validity for nonlinear interpolations:** Limiting the use of nonlinear interpolations to a maximum distance avoids certain artifacts in flat areas and near valley bottoms. It has been found that this limit often depends on the offset between curves, and a factor of 20 is used by default.
- **External area to consider** : To ensure that the quality of the model at the limits of its scope is comparable to that of its interior, it is highly recommended that altimetry information be available in a sufficiently large external area. Information will usually be merged to create an excess scope, and this external area parameter will be adjusted to trim information that is too distant and, therefore, has little influence on the interpolation, thus reducing unnecessary calculations. If this external area is reduced excessively, the DEM limits will be poorly interpolated.

Once the interpolation process is complete, the generated model will be covered by those polygons that mark areas of constant altitude. You can choose to transfer a preset value, inherited from the corresponding field in the polygon database, to the affected cells, or use a value that the DEM itself standardizes across the perimeter that delimits the polygon.

As general characteristics, it is important to highlight that, although the precision of the original data can vary: Z coordinates usually in real format of 1 or 2 decimal places, integer heights of the contour lines, etc., internally all calculations are performed in double precision real format (15-16 significant figures) and the final DEM values are generated in integer format or single precision real format (7-8 significant figures). A significant effort has also been made to introduce procedures that accelerate calculations, while valuing a reasonable use of computer resources.

The format of the generated DEM is, in the implemented version, the MiraMon IMG. It consists primarily of two files: the IMG with the interpolated values corresponding to each cell center, and the I.REL file with the essential metadata: reference system, scope, number of columns and rows, etc., as well as metadata that will add documentation of authorship, quality, process parameters, etc., following ISO 19115 and ISO 19139 standards, and which provide added value in terms of rigor and quality of the generated information.

Experience in calculating DEMs using this methodology has shown that the resolution should be between 1 and 0.5 millimeters at the scale of the original map (source of the contour lines). For example, a 5 m DEM will be generated, and at most 2.5 m, for contour lines from a 1:5000 topographic survey. This resolution avoids, in most cases, the artifacts that occur in very flat areas and with the lack of information regarding the equidistance between the original contours. If higher resolution is required, it is much better to opt for a subsequent densification of the obtained DEM (for example, with the DensRas module in the case of MiraMon).

COMPLEMENTARY METHODOLOGIES

This section details various procedures that have two purposes: to prepare and verify the cartographic bases that will feed the interpolation process described above and to generate a global and objective quality parameter of the DEM: the *root mean square* (*RMS),* from altimetric information that has not participated in the interpolation process.

If a DEM is to be generated for an area spanning several sheets of a map series, it will be necessary to create bases previously merged for interpolation. To interpolation a given sheet, the layers of the eight neighboring sheets will be added. In this merge, it will be verified that there are no discontinuities of the same contour line between the different sheets. At the same time, this condition must be verified for the contours within each sheet, a less likely case, but present in all the real-life examples analyzed by the authors. It is also necessary to verify that there are no intersections between different contour lines, since in this case the interpolation would produce much more visible artifacts than if the previous topological problems were not corrected.

If ridge and valley lines are used as additional altimetric information, it must be verified that the Z coordinates of the 3D vertices are within the heights of the neighboring contour lines. In the applications generated by the authors (detailed in the following section), it was decided to use them solely as an indicator of local maxima and minima, due to the excessive inconsistency found between the Z coordinates and the contour lines. This inconsistency was clearly detected visually, but an initial analysis can be automated by transforming the vertices into points and using the height consistency verification procedure detailed below.

To verify the overall error of the DEM, it is necessary to use as test points the elevations or other point objects (geodetic vertices) that have not participated in the interpolation process. First, it is necessary to discard those elevations that are inconsistent with the contour lines. To do this, polygons are created defined by consecutive contour lines and by a frame that surrounds the scope of the DEM. Each polygon must inherit the attributes of the contours that surround it and occasionally the “non-attribute” of the frame. If using the 'point to polygon' algorithm (e.g., *Burrough* (1998)) we transfer the heights of the polygons to the point, we can deduce which heights are erroneous, or at least inconsistent with respect to the curves (perhaps it is the curves that have the error). Those heights with an altitude not included in the interval of the two curves that surround it are classified as erroneous, or if the height is surrounded by a single curve and the frame and exceeds the equidistance. For example, if we have curves every 5 m, a height of 247.8 m must be between curves 245 and 250 or beyond a supposed curve of maximum height of 380 m, we should not find heights greater than 385 m. As previously mentioned, this methodology is also valid for detecting erroneous vertices of linear objects other than the curves themselves.

Once the erroneous heights have been filtered out from the curves used, the DEM altitude value is transferred to the height at the exact location of the height, in order to compare (obtain the difference) the actual height of the height with the altitude estimated by the interpolation. To obtain the DEM altitude at the exact coordinates of the height, which presumably will not coincide with the center of the cell, it is more appropriate to perform a 4-neighbor (bilinear) or 8-neighbor (bicubic) interpolation than a simple nearest neighbor query. From these altitudes of the interpolated model, we can obtain the RMS.

$$RMS = \sqrt{\frac{\sum \left(z_{\text{spot}} - z_{MDE}\right)^2}{n}}$$

MINISTRY OF EDUCATION OF ANDORRA

Commissioned by the *Department of Medicine Environment* of the *MI Government* Two digital elevation models were generated *in Andorra at 2.5 m and 5 m (by* resampling the first one) and the corresponding derived slope models. Andorra has been an ideal setting to test the developed methodology for two reasons: its extreme relief, an altitudinal range greater than 2000 meters and steep slopes in a region of only 468 $km^{2,}$ and the possibility of having all the information from a 1:5000 3D topographic map. Although a resolution of 1 millimeter is recommended on the map scale, in this case a resolution of 2.5 meters was chosen, for the reasons already explained of a particularly abrupt relief and for greater functionality in the use of not excessively large files and reasonable calculation times.

The basic information was imported from the 1:5000 digital topographic cartography provided by the *Cartography and Topography Area of the MI Govern d'Andorra.* Specifically, all contour lines were extracted (with a 5m offset on secondary contours), all altimetric heights, and those bases that indicated valley floors: rivers and streams. During the generation of the DEM, some errors were detected in this base information, such as contour lines of variable altitude, inconsistencies between some heights and curves, and topological inconsistencies between topographic sheets, which were resolved manually.

The calculation was performed for each of the 74 sheets of the 1:5000 cartographic base. As explained in the **Supplementary Methodologies,** the bases of the 8 neighboring sheets also participated in the interpolation of each sheet. Thus, by merging the 74 DEMs, a seamless DEM was obtained.

Based on more than 22 000 independent elevations calculated by the model, a quality test was performed, which showed that 68 % of the points had an error of less than 1.3 m in altitude, while 99% of the points had an error of less than 3.3 m in altitude. Given the topographic characteristics of the Andorran territory, the generated DEM is considered to be of high quality.

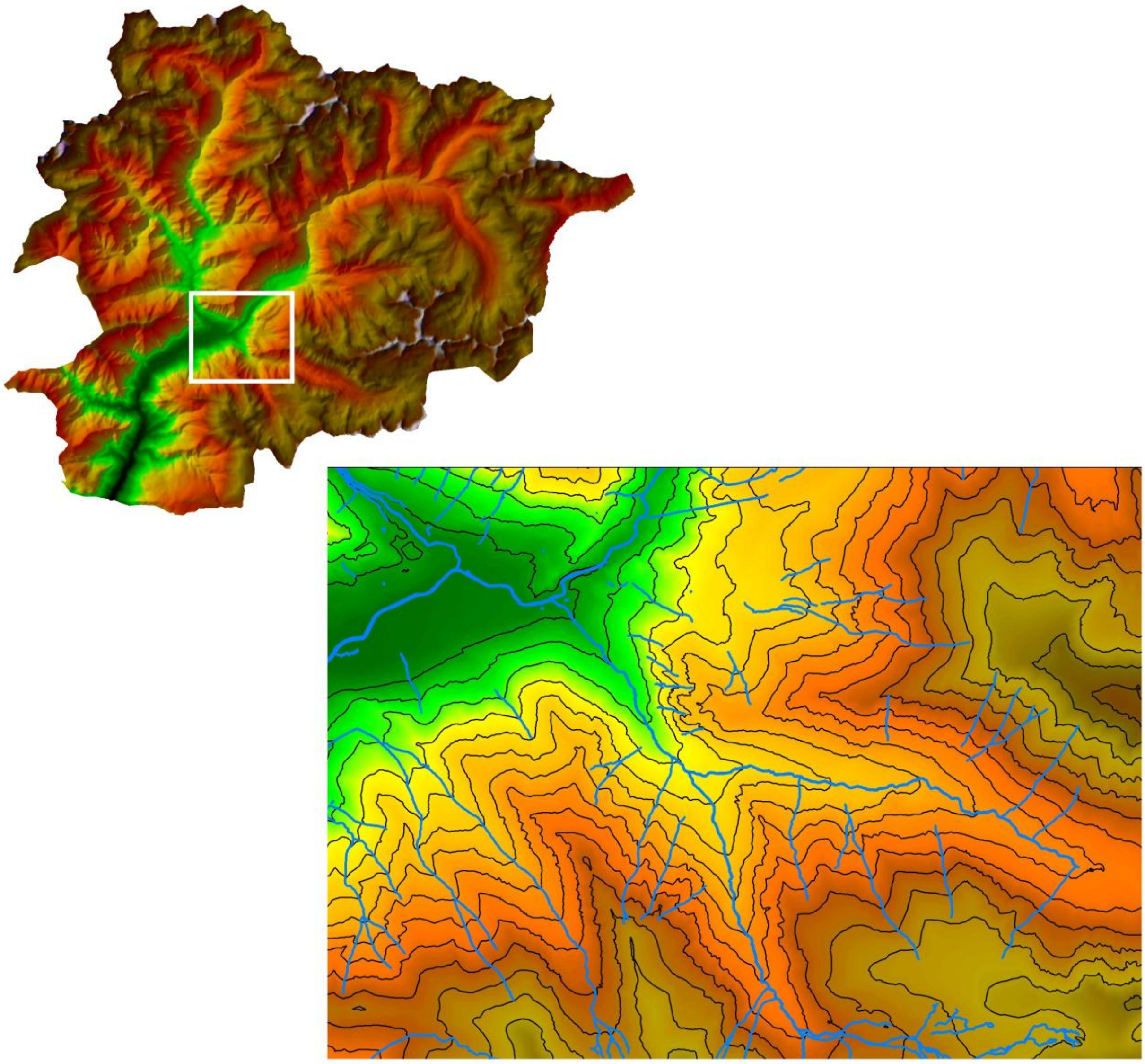


Figure 4. Digital Elevation Model of Andorra (shaded) and detail of a central area of the MDE (without shadows) with superimposition of contour lines and hydrography

MDE OF LA GARROTXA

The Garrotxa region, a mid-mountain area in the interior of the province of Girona, covering approximately 735 km² and with an altitude range of approximately 1 400 m, was the second area where the methodology presented in this work was thoroughly tested. Thanks to the support of the Department of Environment and Natural Resources *(Departament de Medi Environment and Habitatge* of the *Generalitat of Catalonia* and the *Consell Comarcal de la Garrotxa* and the cartography prepared by the *Institute Cartographic of Catalonia (ICC),* The authors generated a digital elevation model at 2.5 m and the derived slope model at the same resolution.

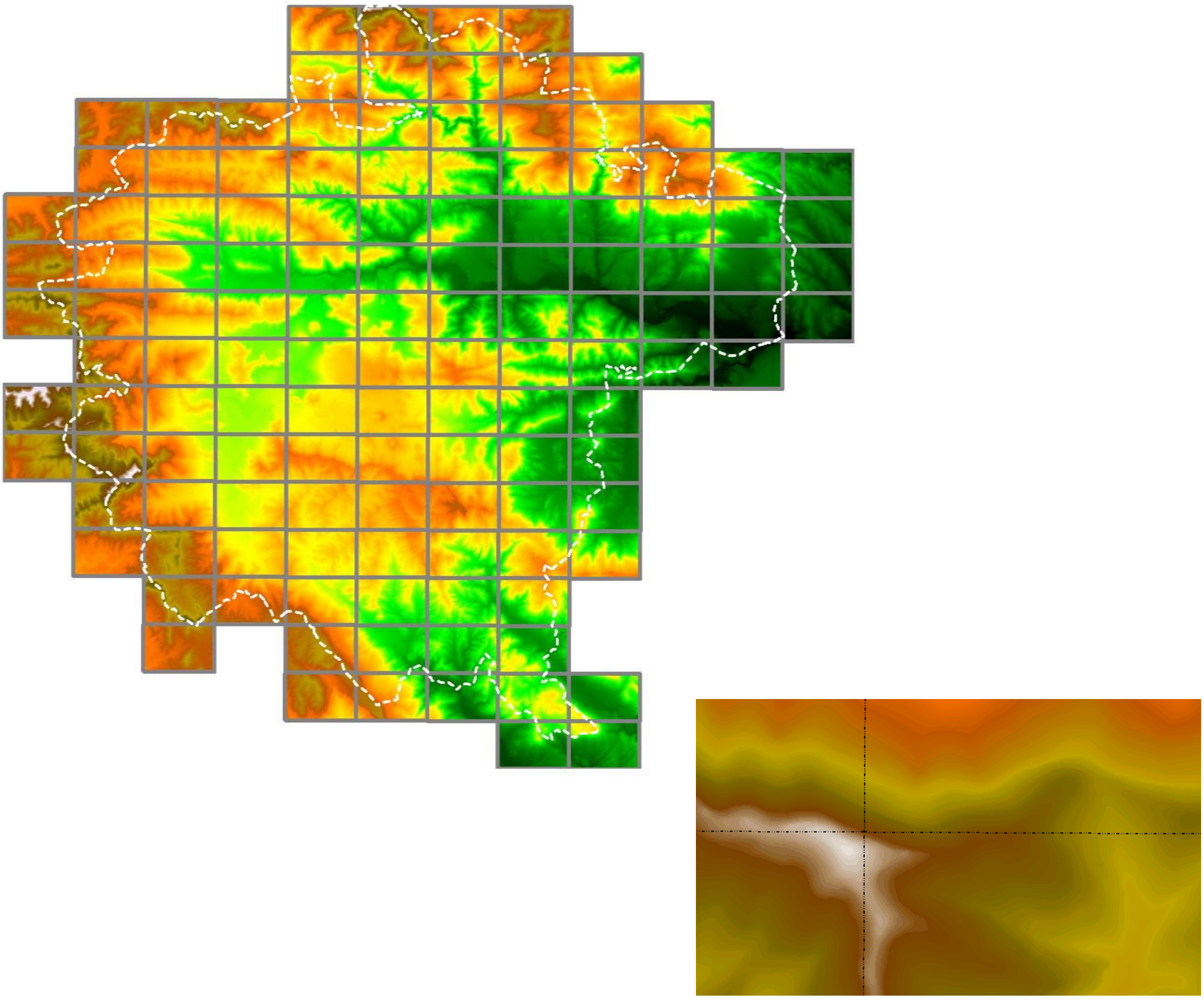


Figure 5. Digital Elevation Model of La Garrotxa. Left: The division into sheets of the 1:5000 cartographic series and the boundaries of the region are shown. Right: Detail showing the continuity between sheets.

The master and secondary contours (equidistance at 5 m) of 127 sheets of the ICC 1:5000 topographic survey, version 2, corresponding to the region were used as a source of altimetric information. Hydrographic layers were used as an additional source of information, and around 72 300 of the 72 569 elevations available on these 127 sheets were used as a validation test. The reason for discarding approximately 250 elevations was their inconsistency with the nearest contour lines. Likewise, some topological problems that surfaced when artifacts were observed in the generated model were corrected. These disappeared when their causes were corrected.

Consequently, 127 DEMs were obtained, with RMS per sheet ranging from 0.77 m to 1.42 m and an overall average of 1.04 m. The merged DEM from the 127 sheets was generated without discontinuities in the overlapping areas and, even more indicative of its quality, without any discontinuities in the derived slope model.

CONCLUSIONS:

It has been demonstrated with two applications (Andorra and La Garrotxa) that the interpolation procedures presented in this work are a perfectly valid methodology and that from the classic and still very common sources of altimetric information, a high quality product can be generated, which in turn allows some topological problems and coherence errors of the original sources to emerge, so that the method can be an indirect tool for validating cartographic sources.

Although the interpolation methods presented here individually correspond to traditional algorithmic tools, the authors introduce new features in their combination, choosing the most appropriate ones according to the morphological situations of the relief and a rigorous analysis of the quality of the generated product.

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