Quality Assessment of Digital Terrain Model

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***Abstract*—The paper presents a study realized for a better understanding of the quality of a digital terrain model; The possibility of modeling the spatial distribution of errors and the land-error relationship are analyzed. A modality of modeling is proposed in the form of a regression equation whose variables are represented by certain parameters hereinafter referred to as field parameters. By applying this regression model, the regression coefficients corresponding to each parameter are obtained, and with these coefficients a regression equation is obtained which can be used to generate an error surface. The quality of this error surface can be evaluated using statistical moments, minimum, maximum error, average error and standard deviation.**

***Index Terms*—digital terrain model, regression model, spatial distribution, terrain parameters.**

I. Introduction

Despite the increasing concerns of recent decades to understand and quantify uncertainty within the digital terrain model, knowledge about digital model errors is still in its early stages and the integration of this knowledge into spatial modeling applications is being developed to a limited degree, the assessment of the quality of the digital terrain model is generally summarized to the value of the average square error (RMSE - Root Mean Square Error).

The average squared error is an estimator that implies that the errors are uniform within the digital model when in reality they are dependent on the terrain features (these characteristics are not uniform so the errors are not uniform, they vary spatially and are spatially correlated).

Research on modeling the distribution of these errors has been done by a relatively small number of researchers. Many authors have mentioned the existence of this spatial variation of errors in the digital model, but in their studies they have started from the hypothesis of uniform distribution of errors.

II. Methodologies for Quality Assessment of Digital Terrain Model

Digital terrain models are representations of terrain topography which contain inherent errors that represent uncertainty. Models are often used in analyses without quantifying the effects of these errors, so a systematic study of the quality characteristics associated with an elevation model is required.

Previous research has tended to focus on a certain aspect of quality, such as the quality of the interpolation method, the comparison of different sampling methods, or the quality of data sources.

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An approach is needed that considers all these factors, and evaluates the quality of the final model in relation to the original land surface. A second limitation of previous research is the inconsistent and incomplete way of assessing and describing quality. The authors adopted one, or maybe two of the three quality assessment approaches: visual evaluation, geomorphometric characterization and precision estimation.

The most common approach is to estimate accuracy. It is considered that measuring altitude error is a useful method of quality assessment.

The quantification of altitude errors can be a more attractive method, from a computational point of view, than the general description of the quality obtained through a visual evaluation. However, the digital model is very rarely used only as the source of altitudes for a certain area of interest, but rather the digital model is used as a basis for more complex analyses in the analysis of spatial relations and processes that characterize a topographic surface.

There is no evidence of how one method of quality assessment is better than the other, and which of the methods describes this aspect more clearly; the adoption of the three methods and the provision of a variety of perspectives appear to represent an increased potential for an evaluation and description of the quality as complete as possible.

A. Visual assessment of quality of digital terrain model

Visualization provides useful methods for understanding spatial data in general [12] and also for evaluating their quality [6]. A number of visualization techniques can be applied to digital models and their derivatives to help evaluate quality.

Visualization is a subjective approach to quality assessment, the findings are dependent on how the user chooses to view a model, and these findings are rendered descriptively.

Two-dimensional rendering allows the end user to examine the range and the distribution of altitude values in a digital model; the fidelity of this representation depends on the number of colors in the palette: too few colors do not give enough details, while too many colors can lead to great difficulty to discern the details.

However, this technique is not very discriminatory when applied for viewing digital elevation models. Only a general impression of the topography is provided, and only major errors can be identified with regard to quality assessment [9].

The representation in orthographic projection, also known as pseudo 3D projection, simulates an oblique perspective view of the surface of the digital model. The amount of information transmitted by this technique depends on the direction of visualization and vertical exaggeration [10]. Reference [10] states that "mesh" display is useful for error

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detection; in addition, a second variable or data set can be draped on the surface.

The realism of a map or frame draped over an orthographic representation of the digital model benefits our visual observation of areas that differ from what is expected [9] and that could also be draped with good results representing the digital model derivatives described below.

Reference [21] describes the use of these visualization techniques as being useful for verifying the geomorphological coherence of the land surface representation (channels, ridges).

The representation of the derivatives of the digital model (gradient, aspect) can provide much more useful information about the quality than simply representing the digital model. The terracing phenomenon can be identified by deriving and representing the gradient, while a representation of the aspect can highlight plateaus, ramps and other artefacts arising as a result of interpolation) [1, 9, 10].

B. Quality assessment based on geomorphometric characteristics

The evaluation of the geomorphometric characteristics of the topographic surface allows the use of several methods to evaluate the quality.

Reference [8] determined a series of geomorphometric variables to give a complete and quantitative description of the surface shape in the field of relief shape evaluation.

Geomorphometric variables can quantify some of the problems and artefacts highlighted by visualization, allowing an objective comparison of elevation digital models, however, this approach to quality assessment seems to be undertaken quite rarely.

References [1] and [10] used frequency histograms to identify terracing as an interpolation artefact. A frequency histogram of altitude values often has a "spiky" appearance due to the terracing effect. Some landscapes are naturally terraced, to some extent, or as a result of agricultural practices.

Therefore, a histogram with a "spiky" appearance does not necessarily imply a poorer quality of the digital model, which is why the geomorphological characteristics of the surface must be interpreted in the context of the features of the land surface that is represented.

These techniques seem to be useful in identifying the digital models that are suitable for certain fields of application. For example, geomorphological features might give information about how smooth the surface is, how many false pits are present, how large the pits are, and if there is a tendency for gradient (slope) distribution, possibly caused by some quantification problems.

This information could help the user decide whether a digital model is suitable for a particular purpose, such as hydrological modeling. By examining the frequency of the gradient and aspect distributions, conclusions can be drawn about the fineness of a digital model. Surface texture indices provide an indication of the diversity and roughness of a digital model [11].

There are also various indices of diversity and heterogeneity, commonly used in the field of landscape ecology, which could be used to quantify surface texture.

As described earlier, the "holes" in the surface of a digital model represent a possible artefact of the interpolation process.

These artefacts prevent the automatic running of many hydrological analyses and must therefore be eliminated. There are various algorithms for removing these artefacts, which are reviewed by [14], the most commonly used algorithms in GIS packages are the flood-filling type.

C. Assessment of the accuracy of digital terrain model

The most intuitive way to assess the quality of a digital model is to determine the size of the altitude error. Determining this error for each cell is not a practical operation; a number of control points are chosen from the model whose altitude is compared with the known terrain altitudes associated with these points or with those extracted from a digital reference model.

Thus, one can estimate the characteristics of the error distribution within the digital model by determining the accuracy.

In many cases – due to the time required and sometimes the impossibility to perform measurements on the ground – it is not possible to determine the "true" values of the altitude. Instead of determining the absolute accuracy of the model it is more practical to determine the relative accuracy by comparing the altitude values extracted from the generated model with those known for an adequate number of control points.

There are two issues that need to be considered when using such a method to evaluate the quality of a digital terrain model, namely: what points should be selected and how high accuracy can be achieved.

III. Spatial Distribution of Errors. The Error-Terrain Features Relationship

Given that the errors within a digital model of the terrain are spatial variables and self-correlating, a precision surface (accuracy surface) provides more detailed information on the quality of the digital model than the global estimate given by the average square error.

Because this surface will be a model of the errors within the model, the shape of this surface will be substantially similar to the shape of the surface described by the digital model, namely a two-dimensional string of precision estimates.

Certain types of terrain – steep or devoid of details, generate large errors in the digital model, so it can be assumed that the distribution and size of errors within a digital model of the terrain are at least partially correlated with the geomorphological characteristics of the terrain.

The identification of the relation between the errors of the digital model and the geomorphological characteristics can provide the basis for creating a surface of the precision of a digital terrain model.

The assessment of the accuracy of the digital model gives us an indication of an aspect of its quality. This assessment can also be used to model the effect that the errors associated with the digital model have on future analyses performed based on it.

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In the previous section, the notion of precision was used as a measure of the errors in the digital model, and was quantified as a single value.

This section presents a more detailed description of the accuracy represented as a spatial variation (distribution) of the error within the digital model of the terrain.

The errors are related to the characteristics of the land and assume that they can be modeled in the form of an error surface (the spatial distribution of errors), a surface that can be created by modeling the relationship between errors and the shape of the land.

The analysis of this hypothesis can be structured in the form of the following objectives:

- analysis of the relationship between the errors of the digital model and the terrain characteristics;
- developing a model of the relationships between errors and terrain features in order to generate a variable and spatially correlated error surface;
- analysis of the quality of this error surface.

A. Spatial distribution of errors of the digital terrain model

The description of the errors of the digital model of the field as a single value, a measure of the global accuracy, such as the use of standard deviation, or of the average square error, is advantageous. A single value is easy to calculate and report, and makes the task of comparing digital models an easy thing to do (qualitative comparison between digital models). Several authors recognize that determining a single value of global accuracy has its limitations. Reference [9] argues that a study of the precision of the digital model of the terrain is useful if one investigates the spatial variation of the errors. Reference [18] describes how an overall accuracy estimator does not provide the possibility to identify areas where errors are large, and in this case additional digital model accuracy analysis is required.

Reference [17] states that the mean square error implies that the errors are uniform within the digital model when in reality they are dependent on the terrain features (these characteristics are not uniform so the errors are not uniform; they vary spatially and are spatially correlated).

B. Relationship between digital model errors and field characteristics

It is intuitive that certain types of terrain (with specific geomorphometric characteristics) are better suited to generate a quality digital model (errors are smaller in the case of lands with a less complex structure; digital models of the terrain obtained by photogrammetric means in the areas not covered are much more accurate than those obtained in the areas covered with vegetation.

Numerous studies have been carried out to identify and quantify the relationship between the terrain and the errors of the digital model of the terrain.

Reference [21], evaluating the quality of two digital models, observed large errors in higher areas and smaller errors in lower areas; the error is strongly correlated with the gradient, the appearance and the value of the reflectance of the satellite images, due to the fact that in the areas with high relief shapes a small modification of the stereo model determines large differences in the recorded altitude [16]. The appearance determines which areas are shaded during the capture of the scenes. The values of the reflectance in the case of the aerial images are in relation to the vegetal cover that can hide the real surface of the land.

References [9], [10] showed how the precision of the digital model of the gradient and aspect field can be correlated and generated a regression model to make a prediction of the accuracy based on known values of the gradient and aspect.

C. Modeling the distribution of errors digital terrain model

It is known that the errors of a digital model of the terrain are spatial variables and are dependent on the characteristics of the terrain. Research on modeling the distribution of these errors has been done by a relatively small number of researchers.

Many authors have mentioned the existence of this spatial variation of errors in the digital model, but in their studies they have started from the hypothesis of uniform distribution of errors.

Spatial correlation describes the tendency of the value of a variable in a given position to be similar to the values in the neighboring positions and to decrease in similarity as the distance increases.

Reference [6] has shown that the errors are spatially correlated and therefore a model of the errors of a digital model should not be generated randomly, but taking into account their spatial dependence.

They presented an autoregressive error model generated by repeatedly changing the cell values of a digital model of the network-type field until a spatially correlated error surface was obtained, i.e. an area in which the error values gradually change from one cell to another.

The generation made by them was based on a single global value, mean square error; the values of spatially correlated errors vary after a normal distribution of this value.

There are two coefficients generally used to quantify the degree of correlation associated with a set of values: the index C set by [11] and the index I set by [2] used Moran's index I to simulate the spatial structure of errors associated with a digital model. This index measures the similarity of values at specific distances (lags).

A model of spatial correlation changes can be constructed by calculating this index for a certain number of distance values. Monckton did not detect the presence of spatial autocorrelation in the distribution of errors in his study. However, the results obtained by it can be considered inconclusive due to the low density of the points used, the points were at an interval of 250m or greater. For intervals (distances) smaller than those used by him it is possible to have (detect) autocorrelation.

The studies conducted by [20] involved the use of semi-variance analysis of errors to evaluate the frequency of errors in the form of noise that appears within the model. This allows the determination of an optimally sized filter for the purpose of eliminating (filtering) the random noise, leaving only spatially correlated errors within the model.

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The study did not investigate the nature of the remaining errors, regarding the degree of spatial autocorrelation and the value of the errors due to the particular characteristics of the land.

These examples of modeling the spatial correlation of errors generate error surfaces, values that are spatially variable and correlated, but their distribution is uncorrelated (the distribution of one error is independent of the distribution of another error).

This means that the values of the errors vary, but not in relation to another variable. The apparent relationship between errors and terrain features implies that the surface of errors contains variables that are essentially dependent on each other.

Reference [17] used Kriging interpolation techniques to create a surface using as input data point data, because the interpolation method allows the generation of a second surface consisting of anticipated values of the interpolated values (the method assumes that the spatial variation of the interpolation data is homogeneous for the whole surface), a surface that quantifies the accuracy of the interpolated values.

Also the technique of obtaining a surface by linear spline interpolation described by [10] similarly produces an area of the average squared errors that quantifies the accuracy of the interpolated values.

These surfaces are spatially distributed error models, but they only describe the uncertainty of the estimates made in the interpolation methods used, and therefore they describe the behavior of the values of the mean square error or standard deviation, values that increase as the deviation of the values relative to the input points increases.

These models do not take into account the accuracy of the input data or the nature of the relationship between errors and terrain features.

D. Modeling uncertainty using information about the accuracy of the digital model

Within spatial modeling, the precision, quality and uncertainty of the digital model of the terrain have been investigated since 1990. However, at present, the quality of spatial data sets and how this influences the final product of modeling is not well known.

This is an important remark in the particular case of the digital model of the terrain due to its wide applicability and the large variety of data sets that can be derived from it and to the fact that systematic and holistic studies on the quality of the digital model are missing.

The quality of the digital model of the terrain is given by aspects such as: altitude accuracy, geomorphological characteristics and model limitations.

A number of factors influence the quality of the digital model: data sources, modeling type, modeling density and interpolation methods.

It is necessary to analyze the quality of a digital model both in terms of altitude accuracy and in terms of the quality of the geomorphological characteristics of the terrain. It is also necessary to investigate how the quality of the digital model of the terrain is affected by the uncertainty of the modeling results.

With no precision, there are no obvious ways to quantify quality factors characteristic of a digital terrain model. It is difficult to objectively judge the quality of a data set or analytical model, and it is also difficult to assess what the quality needed for a particular type of application should be. Although we can calculate accuracy indices for a particular model, they are merely estimators of accuracy, and this lack of quality information can be expressed as uncertainty [21].

Errors, inaccuracies and therefore uncertainty exist in all spatial data sets and in all models of analysis [17], [13], [15], and [22]. Using data and results without considering uncertainty can lead to inappropriate decisions [13]. A good understanding of the errors leads to an adequate quality control allowing the model analyzer to control and reduce, perhaps, the errors, which leads to a better understanding of the spatial distribution and the processes, and to an increase of the modeling and optimization analysis strategies [17].

Many authors have proposed strategies for controlling quality and uncertainty [6, 7, and 5]. Accuracy improvement research has been conducted, but they have focused more on measurement errors, namely how to appreciate and express errors, on the propagation of errors at different processing stages, and on how to express quality. Many studies are at the research level and very few are systematic [17].

The statistical moments and the precision surfaces provide limited and indirect information about the uncertainty of the derivatives obtained based on the digital model. Modeling the impact of the quality of the digital model offers more direct information about the uncertainty. Three main techniques were used to model this uncertainty: epsilon bands; error propagation, and stochastic simulation. Stochastic simulations provide a number of random surfaces.

This technique does not ensure that the "real" surface is obtained, but provides some limits between which the "true" surface can be identified. Thus simulation techniques can be used to determine the uncertainty associated with altitude information within a digital model.

A fairly large variety of simulation methods are available [4] and one of the most widely used is Monte Carlo simulation.

The Monte Carlo method can be described as a statistical simulation method that uses a randomly generated set of numbers based on a given statistical distribution.

Any statistical distribution can be used to generate random errors, but the most widely used distribution is the normal Gaussian distribution. When additional information about the error structure of the spatial data set is available, the Gaussian model can be replaced by a more precise statistical representation [6].

In the context of digital terrain modeling, Monte Carlo simulation is based on the principle that the digital model is one of an infinite number of possible representations of the real elevation surface [5]. Each of these possible representations, or achievements, is just as likely to occur, and the digital model is considered to be a randomly chosen embodiment.

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IV. Tools for Assessment of Quality of Digital Terrain Model

In order to quantify the quality of a digital model, it is necessary to develop tools for quantifying and reporting quality and uncertainty.

The methods involved in evaluating the geomorphometric characteristics of the model as well as in determining the accuracy, are summarized below with reference to the use of the *Photo-AddValue* extension, an extension for ArcGIS 9.3, which was developed as a set of tools needed to assess the quality and model uncertainty of the digital terrain model.

The assessment of the geomorphometric characteristics takes into account the general shape of the surface model. The first step is to make representations of the digital model and some derivatives thereof such as a representation of the gradient and the aspect.

The estimation of some geomorphometric indices such as the errors of the level curves (the case of interpolation of a data set derived from level curves), the flatness indices and the volume of the pits (pit volume) within the model represent a quantitative and less subjective way of evaluating the quality of digital terrain model.

The *Photo-AddValue* extension allows the calculation, reporting and storage of these indices that are a function of the character of the terrain as well as the quality of the model, so they should not be used as quality indices when comparing digital models covering different areas.

Accuracy assessment involves comparing altitude values corresponding to a sample of cells within the model with more precise altitude values.

The highest practical accuracy can be obtained by using GPS receivers that allow differential correction of the carrier phase signal. Where this approach is not feasible, data with higher accuracy can be obtained from other data sources such as level curves or points obtained from digital models generated by photogrammetric methods, however we must be aware that these data do not convey the "true" altitude value because these data sources are also subject to errors.

The Accuracy Measures menu of the *Photo-AddValue* extension calculates three precision estimators (standard deviation, confidence level and average error) whose values are reported and stored. These global precision estimators are useful for a quick assessment of the accuracy of a digital model and can be used to compare two or more digital models.

A precision surface that describes the variation in accuracy within the digital model represents a much more detailed description of the accuracy. There is a relationship between the accuracy of the model and the terrain features. A multiple regression model can be used to describe this relationship and to obtain a precision surface. The main steps to achieve this surface, using the *Photo-AddValue* extension, are:

- obtaining the precision estimators (average error, standard deviation, confidence level) and determining the values of the field parameters at the control points;
- determining the coefficients of the regression equation corresponding to the terrain parameters to model the relationship between errors and terrain features;
- generating the precision surface based on the regression equation.

This precision surface provides a detailed representation of how accuracy varies within the digital model and can also be used to simulate uncertainty.

The quality report should be produced for the user's own purposes and for the transmission of information to other users of the digital model of the land. A full quality report should contain the following:

- detailed information about digital terrain model creation process: origin, date and a description of data sources, modeling methods used, software used;
- description of the representation of the relief shapes, the general appearance of the land surface model, as well as the presence of the artefacts;
- geomorphometric indices: the error of the level curves, the flatness index, the volume of the pits;
- precision estimators: standard deviation, confidence level and average error;
- precision surface and derived terrain parameters used in the regression model.

The first three elements should be provided in all quality reports; the last two elements are of a much more complex nature and can only be provided where the quality of the products obtained on the basis of the digital model of the land is of utmost importance.

Table I can be considered as a possible model of quality report.

Table I. Quality Report Model

Model name ___________________ **Date:** __/__/_____ **Author:** _____________	
Description: **- coverage area** **- area description**	
Spatial reference information **Coordinate system:** __________ **Datum:** ___________ **X min:** ______ **X max:** ______ **Y min:** ______ **Y max:** ______ **#Columns:** ________ **#Rows:** ________ **Resolution:** ________	
Data sources ***technical details ***	
Quality assessment ***quality of digital terrain model ***	
Geomorphologic parameters	**Accuracy estimators**
Error surface ***description of this surface***	

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V. Conclusion

Assessing the quality of digital terrain model, as well as modeling the associated uncertainty, is a large and complex field of study and there is great potential for further investigations in certain directions such as:

- determining the appropriate number of control points needed to calculate the precision estimators because the Li equation that was used was not established in order to determine the required number of points in order to determine a precision surface;
- modelling the terrain error relation and the square or cube values of the terrain parameters, taking into account the fact that there could be a nonlinear relationship between them and the model errors depending on the specific surface of the modeled surface. The extension allows the determination of the corresponding correlation coefficients and the insertion of these values in the regression model;
- analysis of the influence on the relation between errors and field parameters of the dimension (radius) of the circular window (5, 10, 20 cells) for extracting the values of the field parameters;
- identification of other terrain parameters to determine the regression equation that models the relationship between terrain features and errors of the digital terrain model.

References

[1] A. Carrara, G. Bitelli and R. Carla, "Comparison of techniques for generating digital terrain models from contour lines", *International Journal of Geographic Information Science*, vol. *11*, no. *5*, pp. *451–473*, May, 1997.

[2] C. Monckton and M. Worboys, "An investigation into the spatial structure of error in digital elevation data," in *1st National conference on GIS research UK, Innovations in GIS*, Keele, U.K., 1993, pp. 201–211.

[3] C. R. Ehlschlaeger and A. Shortridge, "Modelling elevation uncertainty in geographical analyses," in *Advances in GIS Research, Proceedings of the 7th International Symposium on Spatial Data Handling*, M.J. Kraak and M. Molenaar, (Ed.s). London, 1997, pp. 585–595.

[4] C. V. Deutsch and A. G. Journel, *Geostatistical Software Library and User's Guide, 2nd* ed. Oxford, London: Oxford University Press, 1998.

[5] D. G. Rossiter, "Land evaluation. Part 5: risk and uncertainty," SCAS Teaching Series No. T94-1, Department of Soil, Crop and Atmospheric Sciences, Cornell University, 1995.

[6] G. J. Hunter and M. F. Goodchild, "Modeling the uncertainty of slope and aspect estimates derived from spatial databases", *Geographical Analysis*, vol. 29, pp. 35-49, 1994.

[7] G. J. Hunter, "Managing uncertainty in GIS", NCGIA Core Curriculum in GIScience, NCGIA, 1998.

[8] I. S. Evans, "General geomorphometry, derivatives of altitude, and descriptive statistics" in *Spatial Analysis in Geomorphology*, R. J. Chorley, Ed. London: Methuen, 1972, pp. 17–90.

[9] J. D. Wood, "*Measuring and Reporting the Accuracy of Ordnance Survey Digital Elevation Data*", Ordnance Survey Technical Report, Ordnance Survey, Southampton, 1993.

[10] J. D. Wood, "Visualizing contour interpolation accuracy in digital elevation models," in *Visualization in Geographical Information System*, H. M. Hearnshaw & D. J. Unwin, Ed. Chichester, U.K.: John Wiley & Sons, 1994, pp. 168–119.

[11] J. Hartshorne, "Assessing the influence of digital terrain model characteristics on tropical slope stability analysis," in *Proceedings of the GIS Research UK 1996 Conference*, University of Kent, Canterbury, U.K, 1996, pp. 3–27.

[12] H. M. Hearnshaw and D. J. Unwin, *Visualization in Geographical Information Systems*. Chichester, U.K: John Wiley & Sons, 1994.

[13] J. R. Eastman, P.A. K. Kyem, J. Toledano and W. Jin, *Explorations in Geographical Information Systems, volume 4: GIS and Decision Making*. Geneva, Switzerland: United Nations Institute for Training and Research, 1993.

[14] L. W. Martz and J. Garbrecht, "Digital definition of drainage network and subcatchment areas from digital elevation models", *Computers and Geosciences*, vol. *18*, no. 6, pp. *747–761*, June, 1992

[15] M. F. Goodchild, "Data models and data quality: problems and prospects," in *Environmental Modeling with GIS*, M. F. Goodchild, B. O. Parks & L.T. Steyaert, Ed. Oxford: Oxford University Press, 1993, pp. 94–103.

[16] N. Raducanu, *Photogrammetry Course*. Bucharest, Romania: Military Technical Academy Press, 1993.

[17] P. A. Burrough and R. A. McDonnell, *Principles of Geographical Information Systems*. Oxford, London: Oxford University Press, 1998.

[18] P. C. Kyriakidis, A. M. Shortridge and M. F. Goodchild, "Geostatistics for conflation and accuracy assessment of digital elevation models", *International Journal of Geographic Information Science*, vol. *13*, no. 7, pp. *677–707*, July, 1999.

[19] P. Fisher, "Algorithm and implementation uncertainty in viewshed analysis," *International Journal of Geographical Information Systems*, vol. *7*, pp. *331–347*, Aug, 1993.

[20] P. T. Giles and S. E. Franklin, "Comparison of derivative topographic surfaces of a DEM generated from stereoscopic SPOT images with field measurements", *Photogrammetric Engineering and Remote Sensing*, vol. *62*, no. *10*, pp. *1165–1171*, Oct, 1996.

[21] P. V. Bolstad and T. Stowe, "Evaluation of DEM accuracy. Elevation, slope, and aspect", *Photogrammetric Engineering and Remote Sensing*, vol. *60*, no. *11*, pp. *1327–1332*, Nov, 1994.

[22] S. Openshaw, M. Charlton and S. Carver, "Error propagation: a Monte Carlo simulation," in *Handling Geographical Information: methodology and potential applications*, I. Masser & M. Blakemore, Ed. Harlow, U.K.: Longman Scientific and Technical, 1991, pp. 78–101.

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