ERROR ASSESSMENT AND PROPAGATION IN DIGITAL TERRAIN MODELING: A REVIEW

S. Mesbah [1], M. M. Madbouly[2], M. Ghanem [3]*

[1] Arab Academy for Science, Technology, and Maritime Transport. Alexandria, Egypt – saleh.mesbah@aast.edu
[2] Institute of Graduate Studies and Research, Alexandria University, Alexandria, Egypt – mmadbouly@alexu.edu.eg
[3] Institute of Graduate Studies and Research, Alexandria University, Alexandria, Egypt – mahmoud.ghanem@alexu.edu.eg

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ABSTRACT

Digital Terrain Modeling (DTM) is widely used in various applications such as terrain analysis, hydrological modeling, and urban planning. However, the accuracy of DTM heavily relies on the quality of input data and the algorithms used to process the data. Errors in DTM can have significant impacts on downstream applications, such as flood forecasting and land-use planning. Error assessment and propagation in DTM is the process of identifying and quantifying errors in the DTM and evaluating how these errors propagate through downstream applications. This paper provides an overview of error assessment and propagation in DTM, including sources of errors, methods of error assessment, and techniques for error propagation analysis. The paper also discusses the importance of error assessment and propagation in ensuring the accuracy and reliability of DTM and downstream applications.

1. INTRODUCTION

Digital Terrain Modeling (DTM) is a process of creating a three-dimensional representation of the Earth's surface using digital data. DTM has a wide range of applications, including terrain analysis, hydrological modeling, and urban planning. However, the accuracy of DTM heavily relies on the quality of input data and the algorithms used to process the data. Errors in DTM can have significant impacts on downstream applications, such as flood forecasting and land-use planning.

Error assessment and propagation in DTM is the process of identifying and quantifying errors in the DTM and evaluating how these errors propagate through downstream applications. This process is critical to ensure that the DTM is fit for purpose and that the results of downstream applications are reliable. There are various sources of errors in DTM, including measurement errors, interpolation errors, and algorithmic errors.

In this context, error propagation refers to the process of understanding how errors in input data and algorithms propagate through the DTM and affect the accuracy of downstream applications. For example, if there is an error in the elevation data used to create the DTM, this error will propagate through the DTM, affecting the accuracy of downstream applications that rely on the DTM. Understanding how errors propagate through the DTM is critical to mitigate the impact of errors and ensure the reliability of downstream applications

Digital terrain modeling (DTM) is an important tool in various applications, such as flood prediction, land use planning, and infrastructure development. DTM is used to create digital representations of the Earth's surface and its features, such as elevation, slope, and aspect. Some potential applications of DTM:

1.1. Flood prediction: DTM is used to create digital elevation models (DEM) that can be used to predict flood inundation and to identify flood-prone areas (Manfreda et al, 2011). Accurate and high-resolution DTMs can improve the accuracy and reliability of flood prediction models.
1.2. Land use planning: DTM is used to create 3D models of the terrain that can be used to visualize and analyze the landscape (Florinsky, Igor V., 1998). DTMs can help to identify suitable locations for different land uses, such as agriculture, forestry, and urban development.
1.3. Infrastructure development: DTM is used to design and construct infrastructure, such as roads, bridges, and pipelines (Meesuk, Vorawit, et al, 2015). DTMs can help to identify the optimal location and route for the infrastructure and to assess the potential impact on the environment.

* Corresponding author

2. ERROR SOURCES IN DTM

Digital Terrain Models (DTMs) are digital representations of the Earth's surface and its features, such as elevation, slope, and aspect. They are created by processing raw data from various sources such as aerial or satellite images, laser scanning, and GPS surveys. However, DTMs are subject to errors and uncertainties that can affect their accuracy and reliability (Klouček et al, 2015). Some potential sources of errors in DTM:

2.1. Data quality: The accuracy and resolution of the data used to create the DTM can affect the accuracy of the model. Low-quality data or data with errors can lead to inaccurate and unreliable DTMs.
2.2. Interpolation: Interpolation is used to estimate the elevation of the terrain between data points. The accuracy of the interpolation method can affect the accuracy of the DTM. Different interpolation methods have different levels of accuracy, and the choice of the method depends on the type and quality of the data.
2.3. Sampling density: The sampling density of the data used to create the DTM can affect the accuracy of the model. Low sampling density can lead to incomplete or inaccurate representations of the terrain. Sampling density can be improved by collecting more data or by using more sophisticated interpolation methods.
2.4. Model assumptions: The assumptions made in the DTM model can affect the accuracy of the model (Quinn, P. F. B. J., et al, 1991). For example, assuming that the terrain is uniformly sloped can lead to inaccurate representations of the terrain. It is important to account for variations in terrain features such as cliffs, valleys, and ridges.
2.5. Geometric distortion: Geometric distortion can occur in the data acquisition process due to factors such as sensor calibration, atmospheric conditions, and terrain features (Duggin, M. J., and C. J. Robinove, 1990). Geometric distortion can lead to inaccuracies in the DTM and affect its reliability.
2.6. Human error: Human error can occur during the data acquisition and processing stages, such as incorrect data entry, misinterpretation of data, and programming errors. Human error can lead to incorrect or incomplete DTMs.

Understanding and addressing the errors associated with DTM is important to ensure the accuracy and reliability of the model. This can involve improving data quality, choosing appropriate interpolation methods, increasing sampling density, accounting for variations in terrain features, correcting geometric distortion, and minimizing human error (Ferrero, Anna Maria, et al, 2009). DTM is a valuable tool in various applications, but it is important to be aware of the potential sources of errors and to take steps to mitigate them.

3. ERROR ASSESSMENT TECHNIQUES

Assessing the accuracy and reliability of digital terrain models (DTMs) is an important step in ensuring their suitability for various applications such as flood prediction, land use planning, and infrastructure development. Here are some potential techniques for assessing the errors in DTMs:

3.1. Ground truth data: Ground truth data involves collecting data from the terrain to establish the true values of elevation, slope, and aspect (Gorokhovich, Y., and A. Voustianiouk, 2006). This can be done using GPS surveys, laser scanning, or other methods. The ground truth data can be compared with the DTM to assess its accuracy and reliability.
3.2. Cross-validation: Cross-validation involves splitting the DTM data into training and testing sets. The training set is used to create the DTM, and the testing set is used to validate the DTM by comparing it with ground truth data or other reference data (Rodriguez-Galiano et al, 2012). This technique provides a measure of the model's ability to generalize to new data.
3.3. Statistical analysis: Statistical analysis involves comparing the DTM with reference data using statistical methods such as mean absolute error, root mean square error, and correlation coefficient. These methods can provide quantitative measures of the accuracy and reliability of the DTM (Clark et al, 2004).
3.4. Visual analysis: Visual analysis involves comparing the DTM with reference data using visualization tools such as contour maps, slope maps, and aspect maps (Chang, Kang-tsung, and Bor-wen Tsai, 1991). This can provide a qualitative assessment of the accuracy and reliability of the DTM.
3.5. Error propagation analysis: Error propagation analysis involves identifying the sources of errors in the DTM and assessing their impact on the overall accuracy and reliability of the DTM (Kobler et al, 2007). This can help to identify areas where improvements can be made to increase the accuracy and reliability of the DTM.
3.6. Root Mean Square Error (RMSE): This technique calculates the difference between the measured elevation and the estimated elevation for each point, squares the differences, takes the average and then the square root to provide a measure of the overall error (Warren et al, 2004).
3.7. Mean Absolute Error (MAE): This technique calculates the absolute difference between the measured elevation and the estimated elevation

for each point, takes the average, and provides a measure of the overall error (Warren et al, 2004).

3.8. Standard Deviation: This technique measures the variation of the elevation values around the mean, providing an estimate of the level of uncertainty (Warren et al, 2004).
3.9. Coefficient of Determination (R2): This technique measures the proportion of the variance in the measured elevation that is explained by the estimated elevation (Warren, Steven D., et al, 2004).
3.10. Monte Carlo Simulation: This technique involves generating multiple digital terrain models using different values for input data and modeling parameters, and then comparing the results to estimate the level of uncertainty (Daly et al, 1994).

Error assessment techniques are essential for evaluating the accuracy of digital terrain models and identifying sources of error. The selection of a particular technique depends on the specific application and the level of accuracy required. It is important to choose the appropriate technique based on the specific application and the available data.

4. ERROR PROPAGATION

Errors in input data and modeling processes can propagate through the different stages of digital terrain model (DTM) creation, which can affect the overall accuracy and reliability of the model. Some potential ways in which errors can propagate through the different stages of DTM creation:

4.1.1. Data collection: Errors in data collection can propagate through the DTM creation process (Hsieh et al, 2016). For example, if the elevation data is collected using GPS surveys, errors in GPS measurements can lead to inaccuracies in the elevation data.
4.1.2. Data preprocessing: Errors in data preprocessing can propagate through the DTM creation process (Toutin, Thierry, 2004). For example, if the raw elevation data is filtered or smoothed, errors in the filtering or smoothing process can lead to inaccuracies in the final DTM.
4.1.3. Interpolation: Interpolation is used to estimate the elevation of the terrain between data points. Errors in interpolation can propagate through the DTM creation process (Kobler, Andrej, et al, 2007). For example, if the interpolation method used is not appropriate for the type and quality of the data, errors can be introduced into the DTM.
4.1.4. Sampling density: The sampling density of the data used to create the DTM can affect the accuracy of the model. Low sampling density can lead to incomplete or inaccurate representations of the terrain (Flener, Claude, et al, 2013).
4.1.5. Model assumptions: The assumptions made in the DTM model can affect the accuracy of the model (Quinn, P. F. B. J., et al, 1991). For example, assuming that the terrain is uniformly sloped can lead to inaccurate representations of the terrain. If the assumptions are not valid, errors can propagate through the DTM creation process.
4.1.6. Validation: Errors in DTM validation can propagate through the DTM creation process (Hollaus, Markus, et al, 2006). For example, if the DTM is validated using inaccurate or incomplete reference data, errors can propagate into the final DTM.

Errors in input data and modeling processes can propagate through the different stages of DTM creation, which can affect the overall accuracy and reliability of the model. It is important to identify the sources of errors and to take steps to minimize their impact on the final DTM. This can involve improving data quality, choosing appropriate interpolation methods, increasing sampling density, accounting for variations in terrain features, and validating the DTM using accurate and complete reference data.

Error propagation analysis is an essential technique for assessing the impact of errors on the accuracy and reliability of digital terrain models (DTMs). The analysis involves identifying the sources of errors in the DTM and assessing how they affect the accuracy of the model. Here are some potential steps for conducting a DTM error propagation analysis:

4.2.1. Identify the sources of errors: The first step is to identify the sources of errors in the DTM. These may include data quality, interpolation, sampling density, and model assumptions. It is important to identify all potential sources of errors to ensure a comprehensive error analysis.
4.2.2. Quantify the errors: The next step is to quantify the errors associated with each source. This may involve calculating the accuracy of the input data, the accuracy of the interpolation method, the completeness of the sampling density, and the accuracy of the model assumptions.
4.2.3. Propagate the errors: Once the errors have been quantified, the next step is to propagate the errors through the DTM. This involves calculating how the errors from each source affect the accuracy of the DTM. For example, if the input data has a

high level of error, this can be propagated through the interpolation process and lead to inaccuracies in the DTM.

4.2.4. Assess the impact of the errors: The final step is to assess the impact of the errors on the accuracy and reliability of the DTM. This may involve comparing the DTM with ground truth data or other reference data to determine the level of accuracy. It is important to assess the overall impact of the errors to identify areas where improvements can be made to increase the accuracy and reliability of the DTM.

DTM error propagation analysis is an important technique for assessing the impact of errors on the accuracy and reliability of DTMs (Sofia et al, 2013). By identifying the sources of errors, quantifying the errors, propagating the errors, and assessing the impact of the errors, the accuracy and reliability of DTMs can be improved, ensuring their suitability for various applications.

5. CASE STUDIES

To illustrate the concepts and techniques discussed, this section presents four case studies that analyze real-world digital terrain models and assess their errors using various methods.

5.1. "Accuracy assessment and correction of a LIDAR-derived salt marsh digital elevation model" by Christine Hladik and Merryl Alber (2012): In this study, the authors used a LIDAR-derived DEM for the salt marshes surrounding Sapelo Island, GA obtained with a state-of-the-art Optech Gemini ALTM LIDAR system with a high laser pulse rate frequency of 125 kHz and advanced IMU/GPS technology, and evaluated its accuracy with elevations collected using real time kinematic (RTK) GPS (Hladik et al, 2012).

5.2. "Assessing the quality of digital elevation models obtained from mini unmanned aerial vehicles for overland flow modelling in urban areas " by João P. Leitão et al. (2016): This study evaluated whether DEMs generated from UAV imagery are suitable for urban drainage overland flow modelling. Specifically, 14 UAV flights were conducted to assess the influence of four different flight parameters on the quality of generated DEMs (Leitão, João P., et al, 2016).

5.3. "Accuracy Assessment of Digital Elevation Models (DEMs): A Critical Review of Practices of the Past Three Decades " by José L. Mesa and Francisco J. Ariza-López (2020): An analysis of almost 200 references has been carried out in order to obtain knowledge about the DEM (Digital Elevation Model) accuracy assessment methods applied in the last three decades. With regard to grid DEMs, 14 aspects related to the accuracy assessment processes have been analysed (DEM data source, data model, reference source for the evaluation, extension of the evaluation, applied models, etc.) (Mesa-Mingorance et al, 2020).

5.4. “Combined analysis of digital terrain models and remotely sensed data in landscape investigations” by Florinsky, Igor V. (1998): The author presents a review of the combined analysis of digital terrain models (DTMs) and remotely sensed data in landscape investigations. The utilization of remotely sensed data with DTMs has become an important trend in geomatics in the past two decades. Models of more than ten quantitative topographic variables are employed as ancillary data in the treatment of images.

6. MITIGATION STRATEGIES

Mitigating errors in digital terrain modeling (DTM) is essential to ensure the accuracy and reliability of the model. Some potential strategies for mitigating errors in DTM are:

6.1. Improve data quality: Improving the quality of the input data is one of the most effective ways to mitigate errors in DTM (Mesa-Mingorance et al, 2020). This can involve using high-resolution data, collecting data using multiple methods, and validating the accuracy of the data using ground truth data.

6.2. Choose appropriate interpolation methods: Interpolation is used to estimate the elevation of the terrain between data points. Choosing appropriate interpolation methods based on the type and quality of the data can help to reduce errors in DTM (Carrara et al, 1997). There are several interpolation methods available, such as Inverse Distance Weighted (IDW), Natural neighbor, and kriging, each with varying levels of accuracy and suitability for different types of data.

6.3. Increase sampling density: Increasing the sampling density of the data used to create the DTM can help to reduce errors (Reuter et al, 2007). This can be achieved by collecting more data or by using data from multiple sources.

6.4. Account for variations in terrain features: Terrain features such as vegetation, buildings, and water bodies can affect the accuracy of the DTM. Accounting for these variations in the DTM model can help to reduce errors (Clark et al, 2004). For example, using different interpolation methods for different terrain features can help to improve the accuracy of the DTM.

6.5. Validate the DTM: Validating the DTM using ground truth data or other reference data can help to identify areas where errors exist (Dandois et al, 2015). This can be done using statistical methods, visual analysis, or other validation techniques.

6.6. Use error propagation analysis: Error propagation analysis can help to identify the sources of errors in the DTM and assess how they affect the accuracy of the model (Zhang, Wuming, et al, 2016). This can help to identify areas where improvements can be made to increase the accuracy and reliability of the DTM.

Mitigating errors in DTM is essential to ensure the accuracy and reliability of the model (Crosetto, Michele, and Stefano Tarantola, 2001). Improving data quality, choosing appropriate interpolation methods, increasing sampling density, accounting for variations in terrain features, validating the DTM, and using error propagation analysis are some potential strategies for mitigating errors in DTM.

7. CHALLENGES AND FUTURE RESEARCH

Assessing and propagating errors in digital terrain modeling (DTM) can be challenging due to several factors. Here are some potential challenges in error assessment and propagation in DTM:

7.1.1. Lack of ground truth data: Ground truth data is essential for validating the accuracy of the DTM. However, collecting ground truth data can be time-consuming and costly. In some cases, it may be challenging to collect ground truth data due to the location or terrain of the study area.

7.1.2. Complexity of the terrain: The complexity of the terrain can make error assessment and propagation challenging. Terrain features such as steep slopes, vegetation, and water bodies can affect the accuracy of the DTM, and accounting for these variations can be difficult.

7.1.3. Interpolation errors: Interpolation is used to estimate the elevation of the terrain between data points. However, the choice of the interpolation method and the parameters used can affect the accuracy of the DTM. Identifying the optimal interpolation method and parameters can be challenging.

7.1.4. Limited data availability: In some cases, there may be limited data available for creating the DTM. This can lead to incomplete or inaccurate representations of the terrain, which can affect the accuracy of the DTM.

7.1.5. Model assumptions: The assumptions made in the DTM model can affect the accuracy of the model. However, some assumptions may not be valid for certain types of terrain or data, which can lead to errors in the DTM.

7.1.6. Computational challenges: DTM creation and error assessment can require significant computational resources, and the size and complexity of the data can make these tasks challenging.

Error assessment and propagation in DTM can be challenging due to several factors. It is important to identify and address these challenges to ensure a comprehensive and accurate error analysis (Hollnagel, Erik, 1998). This may involve collecting ground truth data, accounting for terrain complexity, choosing appropriate interpolation methods, increasing data availability, validating the DTM, and using appropriate computational resources.

Future research can help to address the challenges in digital terrain modeling (DTM) and improve the accuracy and reliability of DTMs includes.

7.2.1. Improving data quality: Provide new methods for collecting high-quality elevation data, such as LiDAR or photogrammetry. This can involve improving sensor technology, data processing techniques, and validation methods.

7.2.2. Developing new interpolation methods: Develop new interpolation methods that are more accurate and suitable for different types of data. This can involve exploring machine learning and artificial intelligence techniques for improved interpolation.

7.2.3. Accounting for terrain complexity: Design new methods for accounting for terrain complexity, such as vegetation or water bodies, in the DTM model. This can involve developing new algorithms or machine learning models to account for these variations in the terrain.

7.2.4. Validating DTMs using new methods: Create new methods for validating the accuracy of DTMs. This can involve exploring new statistical or machine learning techniques for validating DTMs using reference data.

7.2.5. Error propagation analysis: Develop new methods for error propagation analysis in DTM. This can involve exploring new statistical or machine learning techniques for identifying the sources of errors and assessing their impact on the accuracy of the DTM.

7.2.6. Computational efficiency: Enhance new methods for improving the computational efficiency of DTM creation and error assessment. This can involve exploring new parallel computing techniques or developing new algorithms that are optimized for modern computing architectures.

These areas of research can lead to improved data quality, new interpolation methods, better accounting for terrain complexity, new validation methods, improved error propagation analysis, and improved computational efficiency.

8. CONCLUSION

In conclusion, understanding and addressing error sources in digital terrain modeling (DTM) is essential to ensure the creation of accurate and reliable models for various applications. This paper has discussed the potential sources of error in DTM, including errors in data collection, data preprocessing, interpolation, sampling density, model assumptions, and validation. The paper also discussed strategies for mitigating errors in DTM, such as improving data quality, choosing appropriate interpolation methods, increasing sampling density, accounting for variations in terrain features, validating the DTM, and using error propagation analysis.

Furthermore, the paper highlighted the challenges in error assessment and propagation in DTM, such as the lack of ground truth data, complexity of the terrain, interpolation errors, limited data availability, model assumptions, and computational challenges. Finally, the paper identified areas for future research to address these challenges and improve the accuracy and reliability of DTMs, including improving data quality, developing new interpolation methods, accounting for terrain complexity, validating DTMs using new methods, error propagation analysis, and improving computational efficiency.

This paper emphasizes the importance of understanding and addressing error sources in DTM to ensure the creation of accurate and reliable models for various applications. By applying appropriate strategies for mitigating errors and conducting comprehensive error assessment and propagation analysis, researchers and practitioners can ensure that DTMs are accurate and reliable for their intended applications.

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