

HIERARCHICAL MULTIREOLUTION TERRAIN TIN GENERATION USING WAVELET FILTERING

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ABSTRACT

We present an analysis of the filtering capabilities of wavelet and fourier transforms as they apply to terrain model generation. Additionally, we highlight the benefits of wavelet filtering in automatically producing approximations that progress from user-specified coarse to fine resolutions in a terrain model. In our previous work, we used wavelet filtered data in conjunction with a hierarchical triangulation technique to create a set of increasing resolution models. We now describe an approach that no longer is built from right angle triangles but generates triangular irregular networks (TINS) with automated control of triangle properties such as "sliveriness". This method uses a tunable filtering scheme to retain the dominant terrain features at each level and maintains hierarchy. The hierarchical tree could then be used in a real-time application to create an eyepoint specific multiresolution terrain representation. This automated terrain model generation procedure is implemented with real elevation data and the results presented are the relationship between the number of triangles created and the accuracy of the triangular models along with 2D and 3D plots of the resulting triangulations.

AUTHOR BIOGRAPHY

Dr. Venkat Devarajan has been an associate professor of Electrical Engineering at the University of Texas at Arlington (UTA) since March 1990 where he conducts research in visual systems technology and collaborative virtual prototyping and teaches course in Digital Photogrammetry and Computer Vision. Earlier, he was an Engineering Project Manager at LTV Missiles and Electronics (now Lockheed Martin Vought Systems) where he led the development of the first photo-based mission rehearsal system (TOPSCENE) and the associated data base system called ADAPTS for the US Navy. He has over 25 years of experience in several aspects of visual systems development. Besides performing research in this field at UTA, Dr. Devarajan has also been a visual systems technology consultant to the US Navy, the DIA, Loral Vought Corp., McDonnell Douglas Training Systems Corp., Science Applications Int. Corp., and Hughes Training Inc.

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INTRODUCTION

Accurate and efficient terrain modeling is an important aspect of visual simulations which rely on cues from the surface representation to maintain or enhance the user's perception of the environment. In applications where a large area of interest may be traversed and the eyepoint perspective is constantly changing the ability to represent the terrain at multiple resolutions can provide an advantage in rendering. The development of such multiresolution surface models is still a research issue (De Floriani et. al., 1996).

Increases in the resolution of terrain data along with the goal of broader and more realistic coverage forces greater technical challenges in the area of terrain modeling. Availability of higher resolution data sets coupled with more encompassing areas of interest increase the complexity in determining the number of polygons needed to generate a high resolution model. Most importantly, the process needs to be automated in the interest of cost. Achieving realism does not necessarily imply a global increase in the number of polygons required. For example, if an area of interest is relatively planar (or distant), then failure to minimize the number of polygons used for its representation will likely detract from representing detail in highly varying (or close) regions. Therefore, the technical challenge is to automatically generate a terrain model with the greatest possible geometric accuracy while using the least number of polygons.

PROBLEM STATEMENT

A navigable multiple level of detail (LOD) database of the terrain must be created as accurately and automatically as possible. This paper investigates the automated generation of hierarchically structured multiple level of detail databases from discrete data sets, such as digital terrain elevation data (DTED). We compare terrain filter benefits related to the creation of coarse approximations and discuss the use of these approximations in hierarchical triangulated

irregular network (TIN) generation. The problem is to triangulate the data set at a lower density where possible and at a higher density where critical surface features are present.

For quality and flexibility of representation, a hierarchically structured multiple LOD database is desired. Hierarchy dictates that the vertices of a parent triangle are maintained when split to form child triangles. Multiple LOD is needed so that the representation of a region can transition between coarse and detailed resolution as required to represent that region from various viewpoints and ranges. In order to maintain critical features a higher density of triangles is generally necessary. Relevant properties of hierarchical triangulation include: recursive refinement, matching subdivisions, and explicit multiresolution. Detailed explanations for many aspects of this problem can be found in a recent survey paper (De Floriani et. al., 1996).

RELEVANCE OF WAVELETS

The generation of multiple LODs necessitates decimation (reducing the number of samples). In order to avoid artifacts such as aliasing, decimation must be preceded by low pass filtering (Crochiere & Rabiner, 1975). We consider the discrete wavelet transform (DWT) the preferred method of filtering for the application of terrain modeling (Devarajan et. al., 1996, Fuentes et. al., 1996).

Graps (1995) states that frequency analysis according to scale is the principal idea behind wavelet analysis. Analysis by scale is simply control of sensitivity with respect to variation, whereby a smaller scale is tuned to fine features and a greater scale to gross features. In generating a coarse representation of terrain, it is critical that the overall trend of the surface is preserved. This can be achieved using higher scaled wavelet filtering since it tends to concentrate on the slowest part of the data. An appropriately tuned increase in scale results in a decrease in resolution which produces a better estimate of the unknown trend (Misiti, 1996).

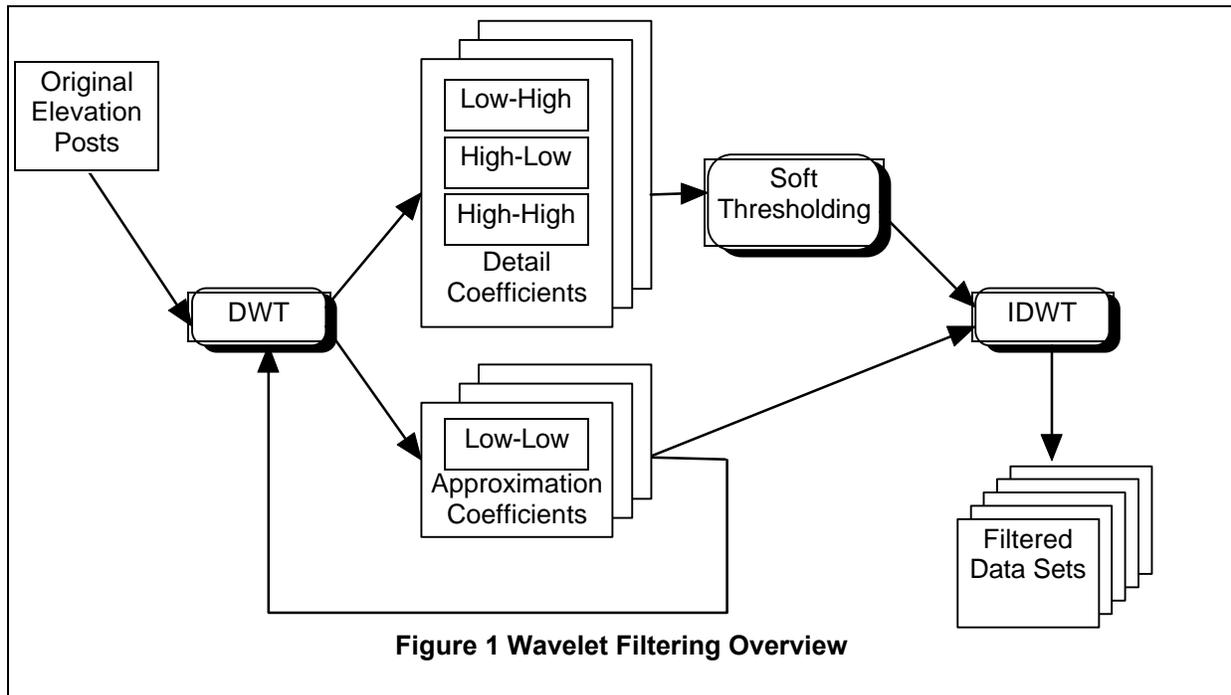
Wavelet processing starts with a basis wavelet function which is applied in variations which are a scaled and/or shifted version of that function. In general, 2D discrete wavelet decomposition will transform an $N \times N$ data set into four sets of wavelet coefficients which are $N/2 \times N/2$ in size. One set (low-low) is referred to as the approximation coefficients since it maintains the overall signal content. The other three sets (low-high, high-low, and high-high) are referred to as detail coefficients since they represent the difference between the approximation coefficients and the original data set at a particular level of decomposition. The process can then be re-applied to the approximation coefficients to generate another level at which additional detail is separated out. The original can be recovered by inverse transforming the last approximation and all the detail coefficients. A series of wavelet filtered data sets can be created by applying a soft or hard threshold to a portion of the details (Donoho 1995). Hard threshold is the common process: any signal below the threshold is set to some predefined value (e.g., zero). Soft thresholding affects the signal above the threshold as well by shrinking the nonzero coefficients towards zero and reducing the effective range of values (Misiti 1996).

Our process for wavelet filtering of the original DTED posts is depicted in Figure 1 and summarized by the following steps:

- 1) Calculate the approximation and detail coefficients for the first processing level by applying a discrete wavelet transform (DWT) to the original data set.
- 2) Apply soft thresholding to the detail coefficients.
- 3) Calculate the first filtered data set by applying an inverse discrete wavelet transform IDWT to the wavelet coefficients.
- 4) Repeat steps 2 and 3 as needed to create filtered data sets for the first processing level.
- 5) Calculate the wavelet coefficients for the next processing level by applying a DWT to the approximation coefficients of the previous processing level.
- 6) Apply soft thresholding to the detail coefficients.
- 7) Calculate the next filtered data set by applying an IDWT to the wavelet coefficients.
- 8) Repeat steps 6 and 7 as needed to create filtered data sets for the current processing level.
- 9) Repeat steps 5 through 8 for each level necessary.

COMPARISON OF WAVELET AND FFT FILTERING

There are many means of filtering 2-D data sets and a "better" method is driven by the goal of the



filtering process. Although frequency and scaling properties of the wavelet made it theoretically the ideal method, we compare it to the traditional FFT approach to confirm this theory and its relevance to the application of terrain databases.

A filtered approximation can be generated by transforming the original data set to another domain, low pass filtering the coefficients, and performing an inverse transform. One means of distinguishing filtered approximations is by virtue of the resultant maximum height error from the original data set. If two filtered data sets have a similar maximum height error, then one can begin to compare visual properties.

Bottom-up and top-down are two approaches to performing triangulations (Lee, 1991). Bottom-up triangulation starts with a high resolution representation and refines the model by decimation. We generate a set of filtered approximations, ranging from coarse to fine, which are used to guide our iterative top-down triangulation process. In the present analysis, we define coarser approximations as having a higher maximum height error and finer approximations as having lower error. The finest resolution used is 1 meter and the resolution is decreased by a factor of two for each representation, up to a 128 meter maximum height error.

The FFT filtered data sets were created by performing a 2-D FFT on the original terrain posts, thresholding the magnitudes, and then performing the inverse FFT. By varying the threshold level, a filtered data set with a particular maximum height error is constructed. Figure 2 shows the original data set and filtered data sets, with maximum height error of 128 meters, for FFT, and wavelet processing. The FFT representation looks roughly similar to the original, but the peaks tend to exhibit a "rolled-off" affect rather than a crisp definition. This is because the sinusoidal basis functions for this method tends to be less suited for approximating data with sharp discontinuities. The wavelet representation has more visually apparent planar regions. For the regions of the terrain that appear to be relatively flat, FFT representation has much more variations than the wavelet.

Since a representation of a terrain surface by triangles is essentially locally planar, it would be advantageous to map the original data set into a form which is also locally planar. This would allow for the use of larger triangular patches for regions

that had little local variation. Therefore, wavelet filtering is the method of choice for the application of terrain modeling.

APPROACH

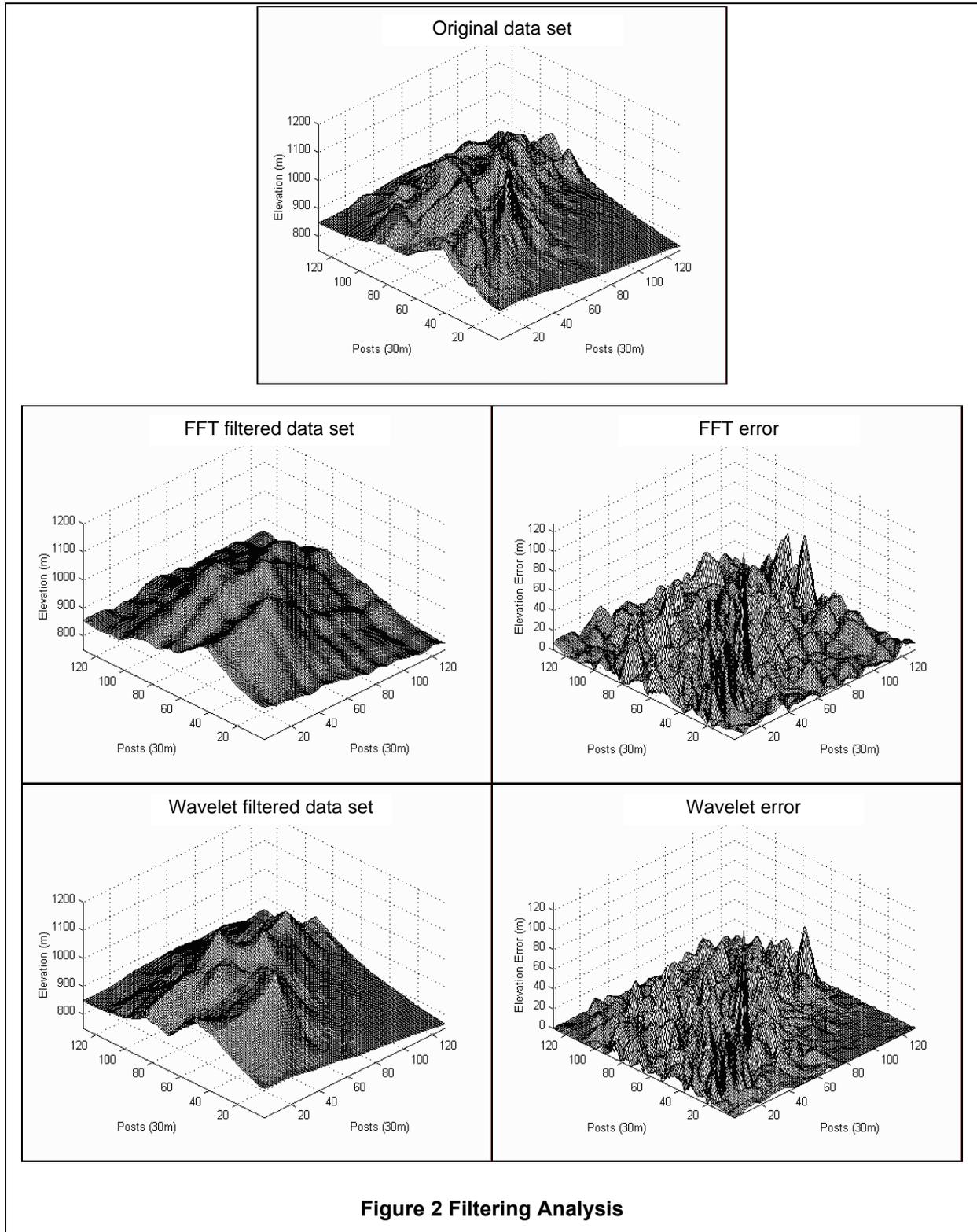
Our approach is motivated by what we consider the two basic issues of terrain modeling. First, the signal processing issue dictates the need for filtering to avoid aliasing (a strictly visual phenomenon). We have presented analysis which clearly validates wavelet filtering. Secondly, the triangle property issue dictates the need for intelligent triangle splitting to minimize quantity, increase accuracy, provide hierarchy, and manage sliveriness. We studied previous methodologies, extended our earlier investigation (McArthur et. al., 1997), and developed a refined approach that addresses both filtering and triangle splitting.

An error driven approach to triangulation guarantees that the error of the triangulation is less than a given value. In a geometry driven approach, the triangles generated must form a given pattern or maintain an acceptable shape. It is well understood that error driven and geometry driven TIN approaches cannot strictly coexist (De Floriani et. al., 1996). Error driven implementations are inclined to produce slivery triangles, while geometry driven will fail to guarantee increasingly finer resolutions. Although it is a desired goal to perform both, in practical implementation this is essentially impossible. Therefore, our approach is to perform triangulation splitting which is *error driven and geometry guided*.

In our initial work (Devarajan et. al., 1996), we analyzed features of wavelet filtering which might be significant with regards to LOD terrain processing. We then considered an implementation which applied wavelet filtering and used right angle triangles to create the models (McArthur et. al., 1997). The application of filtered data sets was performed in a manner which required post height adjustments between LOD models and only one filtered data set was used for each individual triangulation level. The intermediate adjustments meant that the height of a post would almost always be different for each resolution. Although such triangulations don't guarantee surface matching they may be an acceptable solution if geomorphing (Hoppe 1996) is available.

Figure 3 provides the overview of our approach in which we continue our investigation by 1) using TINs to improve quantity/accuracy performance,

2) selecting height values for posts from the original data set to maintain hierarchy in the z-dimension, and 3) using a range of filtered data



sets within each triangulation level. This led to an implementation similar to Adaptive Hierarchical Triangulation (Scarlatos and Pavlidis, 1992), but which differed in the filtering aspect and triangulation details.

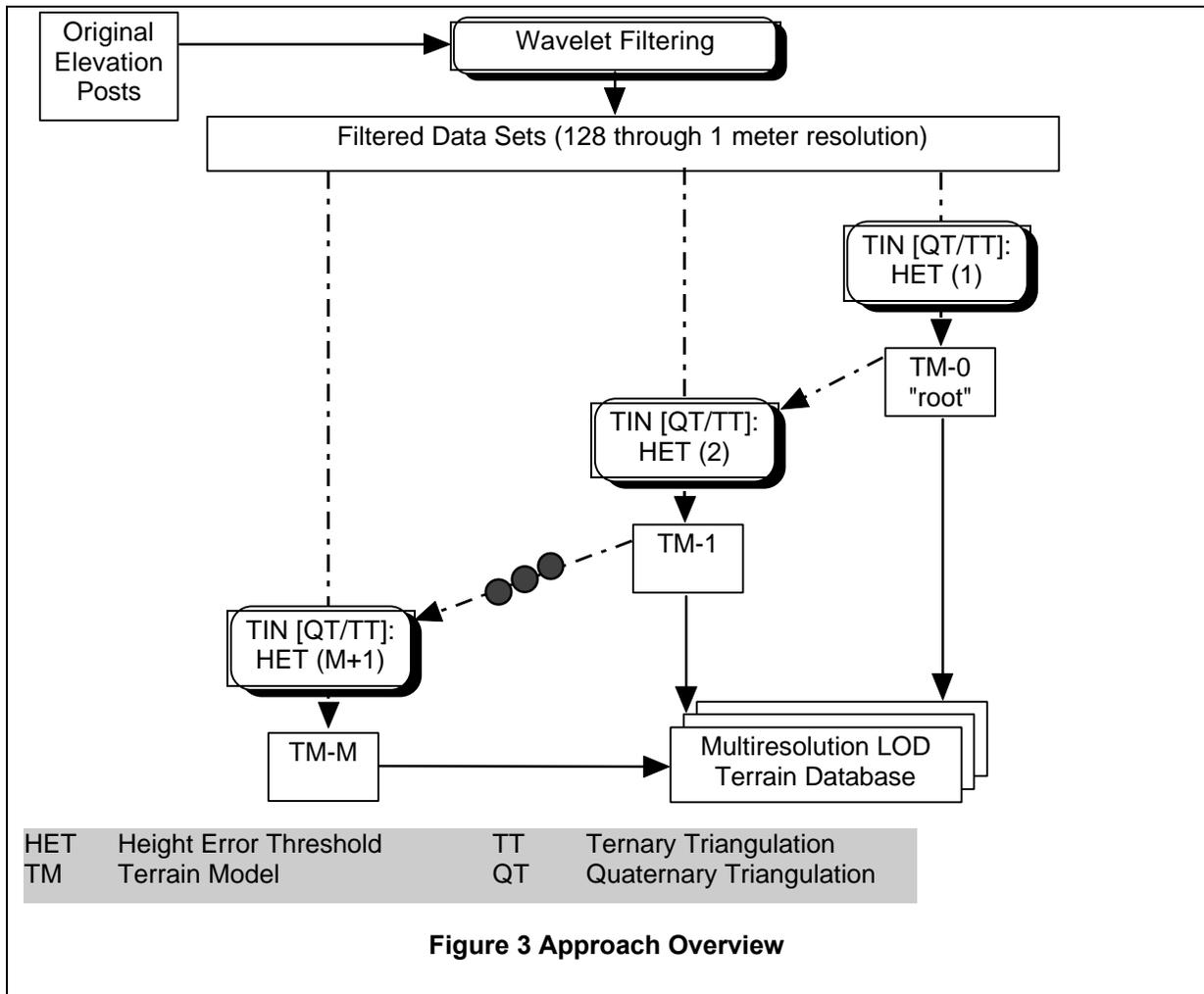
IMPLEMENTATION DETAILS

We start with a square matrix of evenly spaced elevation posts, a set of height error thresholds, and a set of filtered data sets. The error

edges). Basic constraints applied during processing include surface matching to avoid holes and triangle shape to minimize sliveriness.

Initialization

We generate the initial triangulation by splitting the four corner posts of the region along the diagonal and defining the representation as a set of triangles (two), vertices (four), and edges (five).



thresholds applied are decreased for each triangulation level and the resolution of the filtered data set is directly proportional to the size of triangle with which it is used. Key issues of our triangulation scheme are 1) the initial triangulation, 2) when to split a triangle (error driven), 3) how to split a triangle (geometry guided) and 4) the determination of the height value of a newly introduced vertex (matching

These triangles initialize the processing queue. For each height error threshold we refine triangles for which the maximum height error exceeds the threshold. Once refinement for a given threshold is complete, the resulting triangles are added to the processing queue and define a level of the hierarchical structure (terrain model) which makes up the LOD database.

Split Decision

For each triangle of a particular level the maximum height error with respect to the appropriate filtered data set (smaller triangles, finer detailed data set) is determined. If the error exceeds the threshold an attempt is made to split the triangle. The validity of a particular triangle split is governed by the maximum *regularity* and minimum number of posts contained within the triangles resulting from the split. Triangle regularity is the ratio of the maximum edge length to the diameter of the circle inscribed in the triangle (Ciarlet, 1978). Regularity is concerned with shape; an isosceles right triangle has regularity of approximately 2.4, larger values indicate more sliveriness (undesirable long thin triangles). The point count criteria assures that at least one post is contained within or on the edges of the triangle. Lack of concern for the point count could result in triangles for which no accurate height value was available which would violate the signal processing criteria by interpolating beyond the correct post resolution.

Split Methods

Quaternary triangulation is the preferred method, while ternary is included as a last resort to handle cases where quaternary fails. If the split is successful then the new triangles are added to the processing queue, and the new vertices and edges of the split are added to the triangulation definition. In order to maintain a matching surface representation (i.e., to avoid terrain skin cracks), the height of new posts is interpolated from the endpoint of the edge if the edge is not split on both sides. If both edges are split (i.e., doubly split) then the height is the actual post height from the original data set. Due to the surface matching constraint, the height of the split point of an edge which becomes doubly split later in the triangulation is adjusted along with all vertices which are a function of the updated vertex.

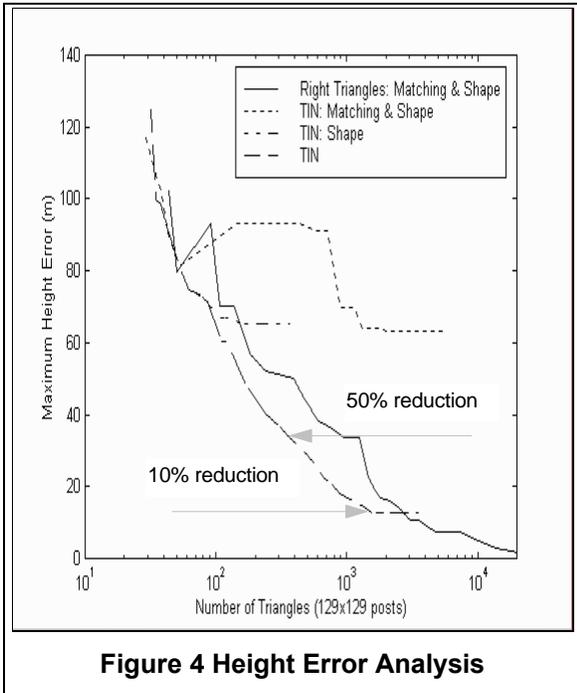
Our quaternary triangulation chooses edge split points based on the height error along the edge and the goal of remaining below the regularity threshold. Initially, we believed that splitting at the point of maximum error along the edge would tend to reduce the maximum height error of the triangle, by adapting the planar representation. This is less true for cases where the edge is not doubly split, since the height of the added vertex is interpolated along the edge. However, we found that additional edge split points needed to be

considered to maintain the desired regularity. We therefore considered several points along the edge for which the height error was large and chose the point closest to the edge center. This improved the regularity, but further analysis showed that at times an edge with much less significant error controlled the split point for an edge with greater error. We chose a scheme that gave more weight to height error for edges which exceed the height error threshold, but at the same time gave more weight to distance from the edge center for edges that are less significant. The results which follow will highlight how this implementation tends to produce a hybrid between right triangles and TINs.

Quaternary triangulation is not always successful due to failure to meet the point count or regularity constraints. In these cases, we attempt to perform a ternary triangulation. This will join each vertex to the interior post for which the error was the greatest. Finally, in cases where a vertex is the post with highest error, then the split is attempted by connecting that vertex to the midpoint of the opposite edge. Where this triangulation fails based on regularity constraints, the triangle is not split.

RESULTS

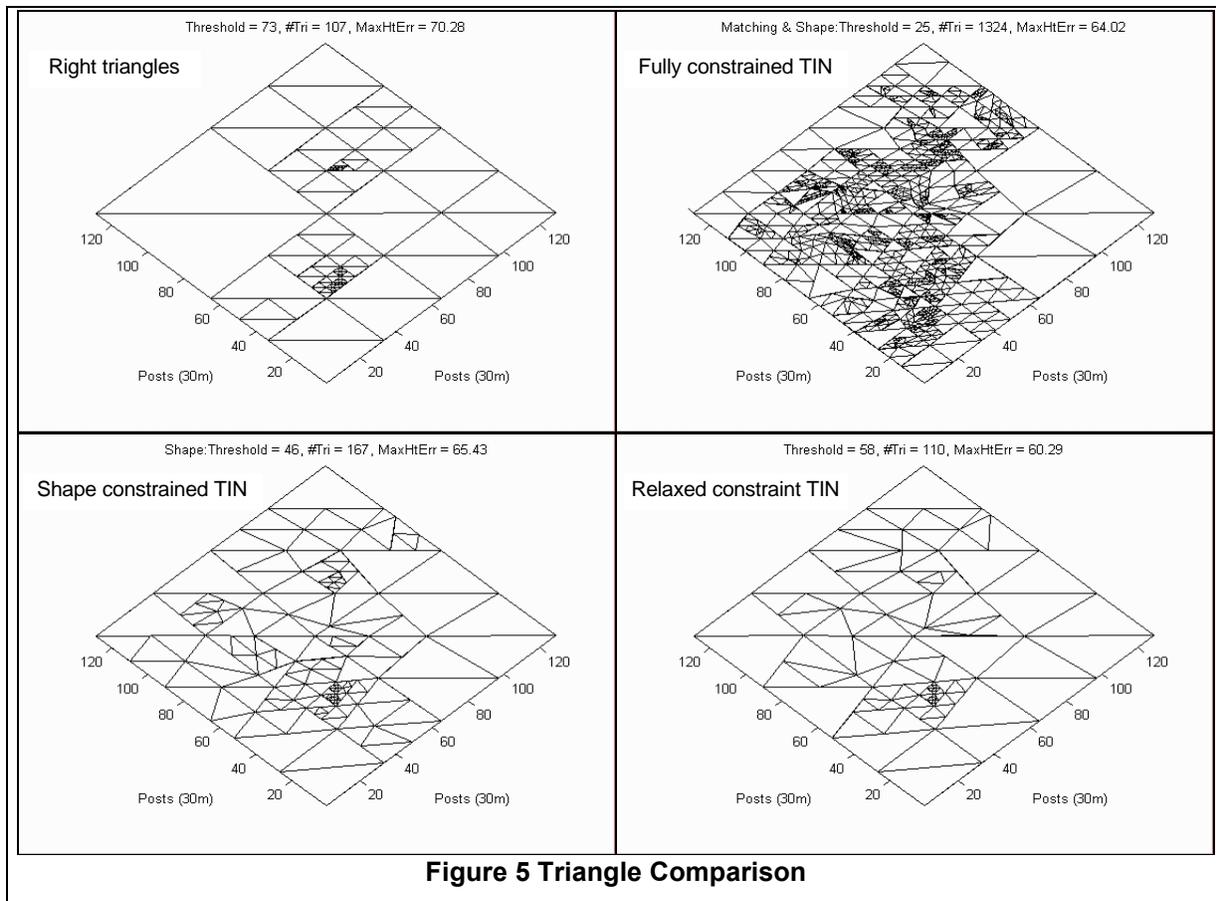
Right triangle splitting naturally imposes the shape constraint, additionally our previous implementation (McArthur et. al., 1997) added the matching constraint. Figure 4 shows the graphical comparison, between right triangles and TINs, with respect to the maximum height error between the triangulation and the original posts. The fully constrained TIN implementation (matching and shape) was our attempt at an *error driven and geometry driven* solution, it performed better than the right triangle method in the generation of coarse models. However, the fully constrained TIN performed poorer below 80 meter height error (adding triangles and increasing error, followed by a slight adjustment). The failure to reduce the height error can be attributed in part to edge points which are interpolated (i.e., effort to maintain matching).



An additional contribution to these results came from the conflict of hierarchical and signal processing demands. We realized that a

relaxation of constraints was necessary to improve the implementation efficiency in terms of the number of triangles. The two other TIN plots of Figure 4 show these results. The first, with only shape constraint (TIN: Shape), performed better than the fully constrained TIN, however it also reached a point from which little reduction in height error was achieved by splitting triangles. The second, with no matching and a relaxed shape constraint (TIN), resulted in favorable improvement. The relaxation of the shape constraint was achieved by maintaining the geometry driven logic while setting the regularity threshold to a large value. These results show approximately 50% reduction in the number of triangles required to meet a maximum height error of 30 meters and 10% reduction for the 15 meter error level.

Figure 5 shows triangulation results for right triangles and each of the TIN results where the maximum height error was closest to 65 meters. The fully constrained TIN generated an extremely large number of triangles. This is because it was unable to achieve height error reduction to 65 meters for all triangles until the threshold was 25 meters. This caused too many other triangles to



be split. For the shape constrained TIN, the results were better, but again the threshold at which this height error was achieved forced more triangles than the right triangle method (167 Vs 107). However, the TIN with no matching constraint and relaxed shape constraint does compare favorably. In this case, a similar number of triangles (110 Vs 107), produced a slightly better height error result (60.29 Vs 70.28). The shape of the triangles for both is similar, the TIN triangles have the perception of slightly rotated or skewed right triangles. This indicates the *geometry guided* effect being properly applied which leads to fewer small triangles early in the process. This in turn provides more splitting options at higher resolutions.

Figure 6 highlights the case where an edge is split on only one side. The error of the split point (P_k) for that edge will be relatively high if the choice of the split point was based on maximum height error of the edge. The new triangles introduced which have edges common to the parent triangle, tend to have their largest height error in the vicinity of this new vertex (P_i). The perceived error exceeds the height error tolerance, thereby causing subsequent splitting. Since the edge of the parent was not doubly split, the same is true for the children and this may lead to a local triangle chain (i.e., the children of the triangle under revision continually fail the height error threshold). Triangles are generated which exceed the height error threshold and can no longer be split. Since the thresholds decrease as triangulations are refined, the result is an increase in triangles with no decrease in maximum height error.

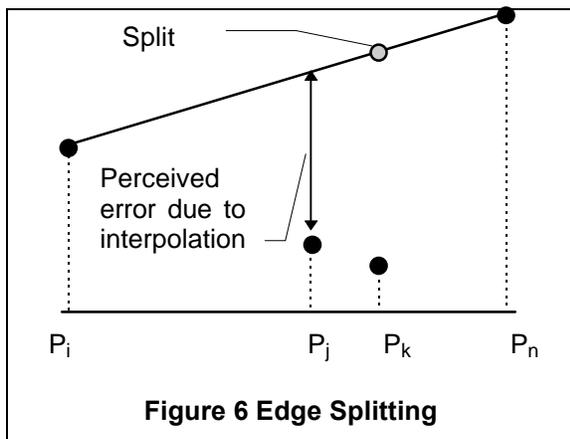


Figure 7 provides a 2D illustration of this effect. The large shaded triangle meets the error threshold, while the three neighboring triangles require additional splitting. Two of these create many small triangles along the shared edge in an attempt to compensate for the perceived error due to interpolation.

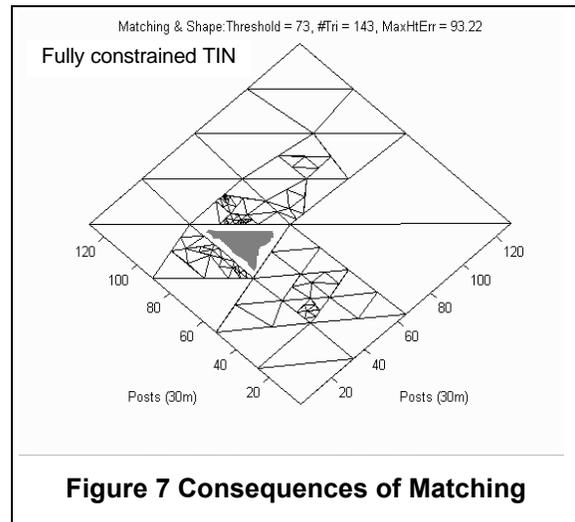
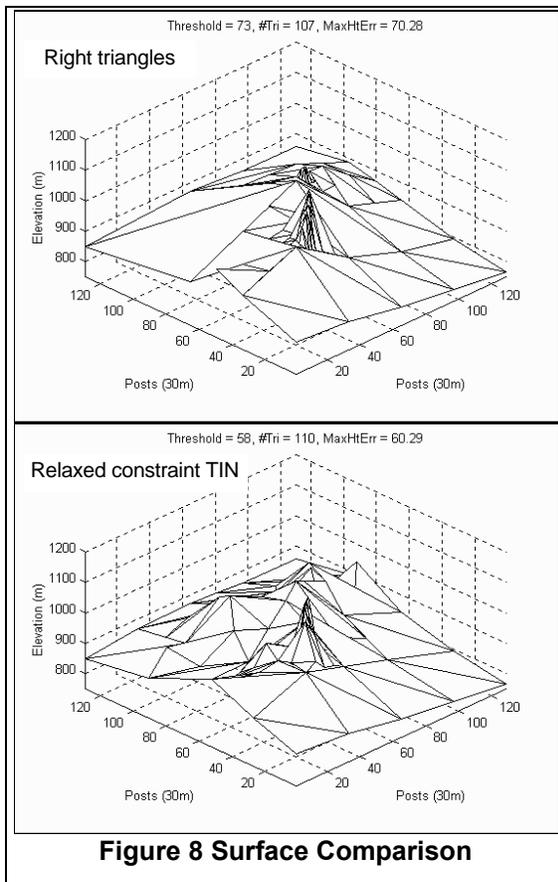


Figure 8 provides a visual comparison of the results between right triangles and TIN for a comparable maximum height error. For a similar number of triangles, the TIN representation appears to have a smoother distribution of detail.

SUMMARY

Signal filtering requirements to avoid aliasing in terrain modeling has been discussed and the choice of the discrete wavelet transform over FFT has been validated. Additionally, we have presented an approach to incorporate wavelet filtering using suitably modified versions of existing triangulation methods. Specifically, we implemented a TIN method which performed triangle splitting constrained by both error and geometry goals. We presented results which showed the problems encountered and additional analysis that led to an improvement in the triangulation efficiency as measured by the number of triangles generated for a given height error in each LOD.



Further work is needed to provide a more automatic means of determining the proper filtered data sets required for a given set of DTED posts. A more elegant wavelet set such as the second generation biorthogonal basis vectors can be used that will guarantee that heights of DTED posts are maintained for critical points in each filtered set.

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